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Radian Corporation
Durham, NC

Prepared for

Industrial Environmental Research Lab.
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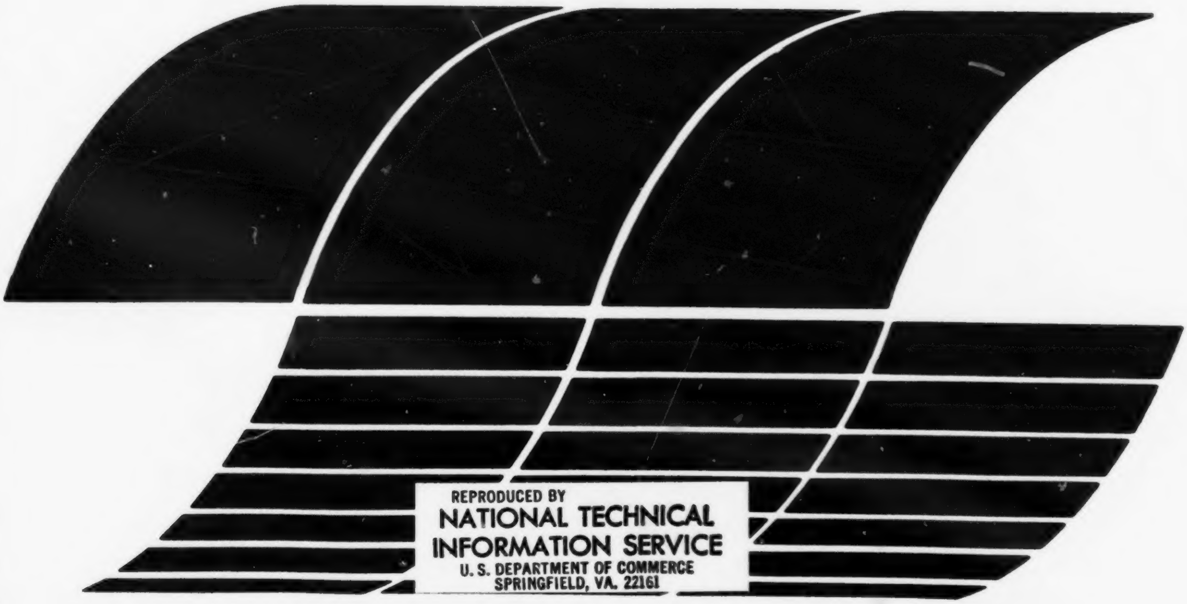

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The report gives results of an assessment of the status of dry flue gas desulfurization (FGD) processes in the U.S. for both industrial and utility applications. The assessment is based on reviews of past and current research, development, and commercial activities. Systems covered include: (1) spray dryers with either baghouse or electrostatic (ESP) particulate collectors, (2) dry injection of alkaline material followed by baghouse or ESP collection of wastes, and (3) other systems, such as coal-alkaline material feeds to a combustor and passage of flue gas through a fixed bed of alkaline material. A summary of dry FGD processes, including key features of three types of dry systems and commercial systems, is provided. Limited economic data are also presented. Conclusions and recommendations are given on the potential role EPA can take to advance the overall environmental acceptability of dry FGD systems as viable SO2 control alternatives.

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Flue Gases	Dust	Dry Processes	21B	11G
Desulfurization	Aerosols	Baghouses	07A, 07D	
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ABSTRACT

The status of dry flue gas desulfurization (FGD) processes in the United States for both industrial and utility applications is assessed. The assessment is based on reviews of past and current research, development, and commercial activities. Systems covered include: (1) spray dryers with either baghouse or electrostatic particulate (ESP) collectors, (2) dry injection of alkaline material followed by baghouse or ESP collection of wastes, and (3) various other systems, such as coal-alkaline material feeds to a combustor and passage of flue gas through a fixed bed of alkaline material.

A summary of dry FGD processes, including key features of three types of dry systems and commercial systems, is provided. Limited economic data are also presented. Conclusions and recommendations are given on the potential role EPA can take to advance the overall environmental acceptability of dry FGD systems as viable SO_2 control alternatives.

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SECTION 1

INTRODUCTION

The purpose of this report is to summarize the status of dry flue gas desulfurization (FGD) processes in the United States, for both utility and industrial application. Throughout this report, dry FGD will be defined as any process which involves contacting a sulfur-containing flue gas with an alkaline material and which results in a dry waste product for disposal. This includes (1) systems which use spray dryers for a contactor, with subsequent baghouse or electrostatic precipitator (ESP) collection of waste products; (2) systems which involve dry injection of alkaline material into contact with flue gas, and subsequent baghouse or ESP collection; and (3) other varied dry systems which include concepts such as addition of alkaline material to a fuel prior to combustion or contacting flue gas with a fixed bed of alkaline material.

This definition of dry systems excludes several dry adsorption or "acceptance" processes, such as the Shell/UOP copper oxide process, or the Bergbau-Forschung adsorptive char process. It was felt that the status of these processes has been documented in other EPA reports and further documentation would not be necessary here.

Also excluded was the regenerable Rockwell Aqueous Carbonate Process (ACP) which, although it does use a spray dryer for a flue gas contactor, does not fit the limitation of this study as being a "throwaway" system. However, the open loop, spray dryer contactor portion of the Rockwell process has been adapted for a "throwaway" system, and as such as been included here.

1.1 REPORT ORGANIZATION

Section 2 summarizes the key features of the three major types of dry FGD processes considered in this survey and includes:

A discussion of the state-of-the-art for each type of process (spray dying, dry injection, and combustion of a coal/limestone fuel mixture).

A process assessment for each type of dry FGD control technology that includes a general process description, key design parameters, and special considerations for the application of the technology on a commercial scale.

A comparison with conventional wet lime/limestone scrubbing technology.

Section 3 presents conclusions and recommendations resulting from this study. Section 4 reviews research efforts in dry FGD prior to April of 1979 in considerable detail, and Section 5 presents a summary of current and on-going dry FGD activities for both research and development and commercial projects. In Section 5 each company involved with dry FGD systems is discussed with respect to the type(s) of systems being developed and marketed; past, current, and future research and development programs; and commercial sales summaries. This report also contains a reference section and an appendix listing metric conversions since virtually all work has been reported in engineering units.*

1.2 TECHNICAL GLOSSARY

Definitions for several terms that are used frequently throughout this report to describe the operation dry FGD systems are defined as follows:

Stoichiometry for dry scrubbing is defined as the moles of fresh sorbent introduced to the system divided by the moles theoretically required for complete reaction with all of the SO_2 entering the system whether or not it is all removed. This is opposed to wet scrubbing where stoichiometry is generally based on moles of SO_2 removed by the system.

Sorbent utilization is defined as the percent SO_2 removal by the system divided by the stoichiometry:

$$\frac{\left[\dfrac{\text{moles } \mathrm{SO_2} \text{ removed}}{\text{moles } \mathrm{SO_2} \text{ entering system}}\right] \times 100}{\left[\dfrac{\text{moles sorbent entering system}}{\text{moles sorbent required to react with } \mathrm{SO_2} \text{ entering}}\right]}$$

$$= \text{(percent) utilization}$$

If one defines the sorbent for a calcium-based system as CaO and the sorbent for a sodium-based system as Na_2O, one mole of sorbent reacts with one mole of SO_x. Consequently, the above expression reduces to:

$$\text{(percent) utilization} = \frac{\text{moles } \mathrm{SO_2} \text{ removed}}{\text{moles sorbent entering system}} \times 100$$

---

* It is EPA policy to report measurements in the International System (SI) of units. For clarity of presentation, units used in this report are those commonly used in engineering calculations in the U.S. Conversion factors are presented in the Appendix.

Since the moles of sorbent do not include alkalinity from other sources such as recycled fly ash, it is possible to see apparent utilizations of greater than 100 percent. That is, the alkalinity in recycled fly ash can react to remove SO_2, so that there are more moles of SO_2 removed than moles of fresh sorbent feed.

A spray dryer is defined as any apparatus in which flue gas is contacted with a slurry or solution such that the flue gas is adiabatically humidified and the slurry or solution is evaporated to apparent dryness. For FGD applications the material dried is often a calcium-based slurry or a sodium solution which reacts with flue gas sulfur during and following the drying process. The spray dryer can use rotary, two-fluid or nozzle atomization, and the vessel can be anything from the back-mix reactor typically used in spray dryer technology to a large horizontal duct.

Dry injection is defined as the process of introducing a dry sorbent into a flue gas stream. This can take the form of pneumatically injecting sorbent into a flue gas duct, precoating or continuously feeding sorbent onto a fabric filter surface, or any similar form of mechanically introducing a dry alkaline sorbent to a flue gas stream.

Coal/limestone combustion is defined as the process of burning a mixture of coal and limestone whereby the SO_2 released from the coal reacts with the limestone to form solid calcium salts that are collected with the ash. Two specific combustion processes are discussed: one involves burning a coal/limestone pellet in a stoker fired boiler, and the other involves burning a pulverized coal/limestone mixture in a low NO_x burner.

SECTION 2

SUMMARY

There are currently three major types of dry FGD systems being developed today: spray drying, dry injection, and combustion of fuel/limestone mixtures. Of these systems, spray drying is currently the only one being developed on a commercial scale. Table 2-1 summarizes the key features of these three main types of dry FGD systems.

Four companies have sold commercial spray dryer-based systems. The Rockwell International/Wheelabrator-Frye joint venture sold the first utility system for the 410 MW Coyote Station to Otter Tail Power Co. Rockwell has also sold a 65,000 acfm industrial boiler system to Celanese. The Joy/Niro joint venture sold a 440 MW system for Basin Electric Co.'s Antelope Valley Station; B&W sold a 500 MW system to Basin Electric for their Laramie River Station. Mikropul Corporation has also sold a dry FGD system, a 40,000 acfm unit, for Strathmore Paper Company's power boiler. The utility systems are expected to start-up in 1981 and 1982, while the systems on the industrial boilers are expected to be operational in 1980. Table 2-2 summarizes the important features of the five current commercial spray drying systems.

Research on dry injection of alkali powders into the flue gas stream showed this technique to be a viable SO_2 control method that required little additional process equipment. However, development and marketing of commercial dry injection systems has not been forthcoming due primarily to sorbent (nahcolite) availability problems.

Preliminary studies have been conducted to determine the potential for reducing SO_2 emissions by firing a coal/limestone pellet in a spreader-stoker boiler. Initial results are promising (75 to 80 percent retention of the available fuel sulfur). EPA funded tests are continuing on industrial size boilers. Another recent study has shown in preliminary results that pulverizing limestone and coal together before combustion in a low NO_x burner can be effective in controlling SO_2 emissions (up to 88 percent SO_2 removal).

Experimental studies have also been carried out to investigate removal of SO_2 by passing the flue gas through a fixed or fluidized bed of alkali sorbent. The relatively large pressure drops encountered in these types of systems make them undesirable for commercial-scale applications. Most fixed bed studies have been aimed at investigating the sorption reaction kinetics.

TABLE 2-1. SUMMARY OF KEY FEATURES OF DRY FGD SYSTEMS

PROCESS TYPE	SPRAY DRYING/ PARTICULATE COLLECTION	DRY INJECTION/ PARTICULATE COLLECTION	COMBUSTION OF COAL/ LIMESTONE FUEL MIX
UNIQUE DESIGN FEATURES	Employs a spray dryer equipped with atomizer(s) to spray sorbent solution or slurry into incoming SO_2 laden flue gas. The spray dryer is coupled with a baghouse (or possibly ESP) to provide collection of fly ash and entrained product solids.	Pneumatic injection of dry alkali sorbent into a flue gas stream with subsequent particulate collection. Injection point varies from immediately after the boiler to just upstream of the collection device (Baghouse or ESP). A baghouse is usually employed as considerable SO_2 removal occurs across the filter cake collected in the bag surface.	The most promising technologies in this area appear to be 1) combustion of a coal/limestone pellet in a spreader stoker boiler, and 2) combustion of a coal/limestone fuel mixture in a low-NO_x burner. The lower adiabatic flame temperature resulting from the two-stage combustion scheme employed in both technologies appears to increase the available limestone reactivity.
REAGENT(s) USED	Sodium carbonate, lime, trona ($NaCO_3$ $NaHCO_3$ $2H_2O$) and limestone have all been tested. Planned commercial systems will use sodium carbonate or lime.	Sodium-based alkalis: sodium carbonate, sodium bicarbonate, trona and nahcolite (60-70% $NaHCO_3$). Lime and limestone have been investigated but both require 600+°F flue gas for significant SO_2 removal.	Limestone (Pellet also requires some type of binder).
RANGES OF REAGENT UTILIZATION	80 to 100% for sodium-based alkalis. 30 to 50% for lime on a "once-through" basis. 80 to 90% for lime with partial recycle of product solids. 20% or less for limestone. Reagent utilization is a strong function of the outlet temperature of the gas; utilization increases as the dryer outlet temperature of the gas approaches its adiabatic saturation temperature.	(Baghouse systems) 40 to 60% for nahcolite, sodium bicarbonate at highest SO_2 removal conditions. 20% or less for limestone even at high flue gas temperature. Utilization increases at higher gas temperatures and is a function of sorbent feeding method.	Ca:S ratios of 7:1 have been used in coal/limestone pellets while a 1:1 ratio was used for the low-NO_x burner tests.
RANGES OF SO_2 REMOVAL	(For inlet SO_2~1000 to 2000 ppm) 80 to 90% for sodium-based alkalis. 45 to 60% for lime on a "once-through" basis. 80 to 85% for lime with partial recycle of product solids. Less than 30% for limestone.[a]	60 to 90% for sodium-based alkali systems depending on stochiometric ratio, flue gas temperature and method of feeding. 90% removals have been achieved with nahcolite at 290°F temperatures. 20 to 30% for limestone at high temperatures (600+°F).	Coal/limestone pellets captured 75 to 80% of the available sulfur in the fuel. Preliminary results in tests with low NO_x burners indicate that 80% retention is achievable.
PARTICULATE REMOVAL	Both baghouses and ESP's have consistently achieved 99+% removal of entrained product solids and fly ash. Baghouses have the advantage of providing for additional SO_2 removal across the filter cake that collects on the fabric surface. However some reports claim it is possible to more closely approach the adiabatic saturation temperature of the gas with an ESP downstream of the spray dryer.	Dry injection systems with baghouses remove 99+% of entrained product solids and fly ash. ESP's demonstrate 99+% removal also, but SO_2 removal is much lower than in baghouses. Also the increased inlet-grain loading will affect ESP sizing.	Combustion of the coal/limestone fuel mixture will result increased particulate loading.
SPECIAL PROBLEMS OR ADVANTAGES	Spray drying results in a dry easy to handle waste product. However, when sodium alkalis are used the products are quite water soluble, creating disposal problems. Water and energy requirements are less than for conventional "wet" lime/limestone systems. High sulfur coal applications may be limited but are being investigated further.	The dry product resulting is quite water soluble and leachability and stability problems are likely to occur in disposing the waste solids. The use of relatively inexpensive reagent (nahcolite) and minimal equipment requirements make dry injection economically attractive. The two major drawbacks are the availability of nahcolite in amounts required for commercial applications and the waste disposal problem.	The additional costs of preparing the coal/limestone fuel and removing greater amounts of ash are significantly less than conventional wet scrubbing system costs. However these technologies have only been applied on a small scale industrial type boiler systems.
DEVELOPMENT STATUS	Spray drying is currently the only commercially applied dry FGD technology with 3 utility (400-500 MW each) systems being constructed (startup in 1981; 82 and 83) and two industrial systems to startup in late 1979. Several other companies are conducting extensive R&E programs toward a commercial system.	Although dry injection has been shown to be technically feasible commercial application is at a standstill due to uncertainties in sorbent availability.	Considerable work remains to develop the technologies for commercial scale applications, although industrial commercial applications look promising. EPA is currently funding continued pilot plant testing on industrial boilers and more complete test work on low-NO_x burners has been proposed and is under review by the EPA.
REPORTED CAPITAL COST ESTIMATES	$80 to $120/KW for utility systems (400-600 MW).[b] $1.0 to $1.5 million for industrial systems (10-25 MW).[c] Based on pilot plant scale-up designs.	$25 to $30 million ($50/KW for 500 MW) for 1% S coal with a heating value of 10,500 BTU/lb.[d]	$15/ton to produce limestone/coal pellet.[e]

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TABLE 2-1 (Cont.)

[a] Utilization and removal figures are quite site specific and the given values should only be taken as a general indication of system performance. Removal and reagent utilizations may be lower or higher depending on system design, SO_2 inlet concentration, stoichiometric ratio, flue gas inlet temperature, temperature drop over the spray dryer and fly ash alkalinity.

[b] Source: Janssen and Eriksen, "Basin Electrics Involvement with Dry FGD" presented at EPA Symposium on FGD, Las Vegas, Nevada. March, 1979.

[c] Source: PedCo Inc., "Survey of Industrial Boiler Dry FGD: First Quarter, 1979". EPA No. 600/7-79-067B.

[d] Source: Lutz, S.J., et al., "Evaluation of Dry Sorbents and Fabric Filtration for FGD". EPA No. 600/7-79-005. January, 1979.

[e] Source: Dickerman, J.C., personal communication with Jack Wasser, EPA.

TABLE 2-2. SUMMARY OF KEY FEATURES OF COMMERCIAL SPRAY DRYING SYSTEMS

SYSTEM	GENERATING CAPACITY	SYSTEM DESCRIPTION	SORBENT	COAL	SO_2 REMOVAL GUARANTEE	SORBENT UTILIZATION GUARANTEE	ESTIMATED CAPITAL COST	ESTIMATED OPERATING COSTS
Rockwell/Wheelabrator-Frye @Otter Tail Power Co.'s Coyote Station, Unit 1, Beulah, ND Start up date: June, 1981	410 MW (1,890,000 acfm)	Four Bowen 46 ft. diameter spray towers in parallel, each equipped with three centrifugal atomizers, combined with a multicompartment Wheelabrator-Frye fabric filter with dacron bags, (reverse-air, shaker cleaned). Process known as Open-Loop (no sorbent regeneration) aqueous carbonate process (ACP).	Soda Ash	North Dakota lignite. Average S=0.78% 7050 BTU/lb=HHV 7% Ash	70% for all fuels	[illegible]	$32,000,000 ($78/KW)[a]	$6,580,000/yr $2.5 mils/kwhr)[a] Does not include waste disposal cost.
Joy/Niro @Basin Electric's Antelope Valley Station, Unit 1, Beulah, ND Start up date: April 1982.	440 MW (2,200,000 acfm)	Five 46 ft. diameter spray modules (4 with ducted spare) in parallel, each equipped with a single high horsepower rotary atomizer, combined with a Joy (Western Precipitation) multi-compartment fabric filter with Teflon coated fiberglass bags (reverse-air cleaning). The system also includes a partial recycle of product solids/fly ash mixture.	Lime	North Dakota lignite. Average S=0.78% Maximum S=1.22%	62% for avg. S coal 78% for max. S coal	Not Reported	$49,665,100 ($113/KW)[b]	$2,270,834/yr (0.8 mils/kwhr)[b] sorbent cost (lime) = $1,102,500 ($60/ton basis) Does not include waste disposal cost
Babcock and Wilcox @Basin Electric's Laramie River Station, Unit 3, Wheatland, Wyoming. Start up date: Late 1979	600 MW (2,810,000 acfm)	Four reactors (one spare) operated in parallel, each followed by an ESP. Each reactor is equipped with 12 "Y" jet nozzles which are dual-fluid atomizers that use steam as the atomizing fluid. ESP's B&W Rothemule.	Lime	Wyoming sub-bituminous Average S=0.54% Maximum S=0.81% 8140 BTU/lb=HHV 8% Ash	85% for avg. S coal 90% for max. S coal	Maximum stochiometric ratio of about 1.12	$49,807,000 ($83 $/KW)	$2,571,000/yr (0.7 mils/kwhr)[b] sorbent cost (lime) = $1,396,570 ($60/ton basis) Does not include waste disposal cost.
Mikropul @Strathmore Paper Co., Woronoco, Mass. Start up date: Late 1979	Industrial Boiler (40,000 acfm)	Spray dry followed by Mikro-Pulsair pulsejet baghouse.	Lime	2 to 2 1/2% S	75% on 3% S coal	Maximum stochiometric ratio of 2.75	$1,400,000[c]	$162,000/yr (2.3 mils/kwhr)[c]
Rockwell/Wheelabrator-Frye @Celanese Corporation Cumberland, Maryland Starting Date: Late 1979	Industrial Boiler (67,000 acfm)	One 25 ft. diameter spray tower followed up by a four compartment baghouse. Dry waste product will be mixed with lime and trucked to dumping area.	Lime	1 to 2% S	85%	Not Reported	$1,250,000	NOT AVAILABLE

TABLE 2-2 (Cont.)

[a] Capital cost for complete turnkey installation from air preheater outlet to stack connection, excluding I.D. fans (1977$). Source: Johnson, O.B., et al., "Coyote Station, First Commercial Dry FGD System", Presented at 41st Annual American Power Conference Meeting. Chicago, IL April 23-25, 1979.

[b] Evaluation based on 35-year life, annual plant factor of 75% (1981$). Source: Janssen and Eriksen.

[c] Total installed cost of entire FGD System (1979$). Source: PedCo Inc., "EPA Industrial Boiler FGD Survey: First Quarter, 1979". EPA No. 600/7/79/067B.

[d] Purchased cost of equipment, silos, internal ductwork, slaker, pumps (excludes I.D. fan, installation, ash handling system, and electrical). (1979$).

2.1 PROCESS ASSESSMENT

2.1.1 Spray Dryer-Based Systems

In these systems, flue gas at air preheater outlet temperatures (generally 250 to 400°F) is contacted with a solution or slurry of alkaline material in a vessel of relatively long resident time (5 to 10 seconds). The flue gas is adiabatically humidified to within 50°F of its saturation temperature by the water evaporated from the solution or slurry. As the slurry or solution is evaporated, liquid phase salts are precipitated and remaining solids are dried to generally less than one percent free moisture. These solids, along with fly ash, are entrained in the flue gas and carried out of the dryer to a particulate collection device. Reaction between the alkaline material and flue gas SO_2 proceeds both during and following the drying process. The mechanisms of the SO_2 removal reactions are not well understood, so it has not been determined whether SO_2 removal occurs predominantly in the liquid phase, by adsorption into the finely atomized droplets being dried, or by reaction between gas phase SO_2 and the slightly moist spray dried solids.

Sodium carbonate solutions and lime slurries are common sorbents. A sodium carbonate solution will generally achieve a higher level of SO_2 removal than a lime slurry at similar conditions of inlet and outlet flue gas temperatures, SO_2 level, sorbent stoichiometry, etc. Lime, however, has become the sorbent of choice in many circumstances because of the cost advantage it enjoys over sodium carbonate and because the reaction products are not as water soluble. Through the use of performance enhancing process modifications, such as sorbent recycle and hot or warm gas bypass, lime sorbent has been demonstrated at the pilot scale to achieve high levels of removal (85 percent and greater) at sorbent utilization near 100 percent.

Using a spray dryer for a flue gas contactor involves adiabatically humidifying the flue gas to within some approach to saturation. With set conditions for inlet flue gas temperature and humidity and for a specified approach to saturation temperature, the amount of water which can be evaporated into this flue gas is set by heat balance considerations. Liquid to gas ratios are generally in the range of 0.2 to 0.3 gal/MCF. The sorbent stoichiometry is varied by raising or lowering the concentration of a solution or weight percent solids of a slurry containing this set amount of water. While holding other parameters such as temperature constant, the obvious way to increase SO_2 removal is to increase sorbent stoichiometry. However, as sorbent stoichiometry is increased to raise the level of SO_2 removal, two limiting factors are approached:

1) Sorbent utilization decreases, raising sorbent and disposal costs on the basis of SO_2 removed.

2) An upper limit is reached on the solubility of the sorbent in the solution, or on the weight percent of sorbent solids in a slurry.

There are at least two methods of circumventing these limitations. One method is to initiate sorbent recycle, either from solids dropped out in the spray dryer or from the particulate collection device catch. This has the advantage of increasing the sorbent utilization, plus it can increase the opportunity for utilization of any alkalinity in the fly ash.

The second method of avoiding the above limitations on SO_2 removal is to operate the spray dryer at a lower outlet temperature; that is, a closer approach to saturation. Operating the spray dryer outlet at a closer approach to saturation has the effect of both increasing the residence time of the liquid droplets and increasing the residual moisture level in the dried solids. As the approach to saturation is narrowed, SO_2 removal rates and sorbent utilization generally increase dramatically. Since the mechanisms for SO_2 removal do not appear to be well understood, it is not obvious whether it is the increase in liquid phase (droplet) residence time, or the increase in residual moisture in the solids, or both which accounts for the increased removal.

Unfortunately, the approach to saturation at the spray dryer outlet is set by either the requirement for a margin of safety to avoid condensation in downstream equipment or restrictions on stack temperatures. The spray dryer outlet can be operated at temperatures lower than these restrictions would otherwise allow if some warm or hot gas is bypassed around the spray dryer and used to reheat the dryer outlet. Warm gas (downstream of the boiler air heater) can be used at no energy penalty, but the amount of untreated gas involved in reheating begins to limit overall SO_2 removal efficiencies. Significantly less hot gas (upstream of the air heater) is required to heat, but an energy penalty associated with the decrease in heat load to the air heater comes with bypassing the plant air heater. Figure 2-1, a general flow diagram of a spray dryer based system, illustrates these two "reheat" options.

The spray dryer design can be affected by the choice of particulate collection device. Bag collectors have an inherent advantage in that unreacted alkalinity in the collected waste on the bag surface can react with remaining SO_2 in the flue gas. Some process developers have reported SO_2 removal on bag surfaces on the order of 10 percent (Ref. 13). A disadvantage of using a bag collector is that since the fabric is somewhat sensitive to wetting, a margin above saturation temperature (on the order of 25 to 35°F) must be maintained for bag protection. ESP collectors have not been demonstrated to achieve significant SO_2 removal. However, some vendors claim that the ESP is less sensitive to condensation and hence can be operated closer to saturation (less than a 25°F approach) with the associated increase in spray dryer performance.

The choice between sorbent types, use of recycle, use of warm or hot gas bypass, and types of particulate collection device tends to be rather site specific. Vendor and customer preferences, system performance requirements, and site-specific economic factors tend to dictate the system design for each individual application.

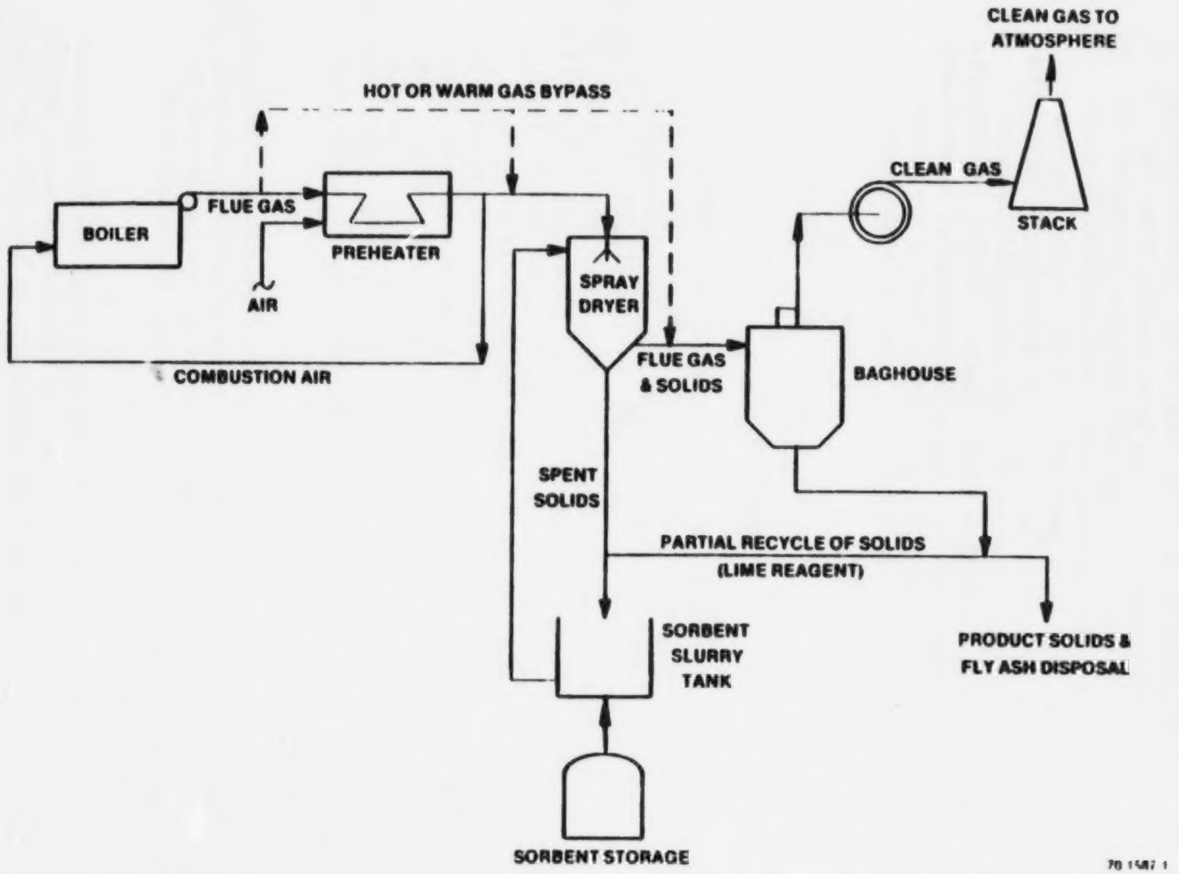
CLEAN GAS TO ATMOSPHERE
HOT OR WARM GAS BYPASS
CLEAN GAS
STACK
BOILER
FLUE GAS
PREHEATER
AIR
SPRAY DRYER
COMBUSTION AIR
FLUE GAS & SOLIDS
BAGHOUSE
SPENT SOLIDS
PARTIAL RECYCLE OF SOLIDS (LIME REAGENT)
SORBENT SLURRY TANK
PRODUCT SOLIDS & FLY ASH DISPOSAL
SORBENT STORAGE
78 1587 1

Figure 2-1. Typical spray dryer/particulate collection flow diagram.

2.1.2 Dry Injection Process

Dry injection schemes generally involve pneumatically introducing a dry, powdery alkaline material into a flue gas stream with subsequent particulate collection. A generalized flow diagram of this process is shown in Figure 2-2. The injection point has been varied from the boiler furnace area all the way to the flue gas entrance to an ESP or bag collector. Most dry injection schemes use a sodium-based sorbent. Lime has been tested but has not been demonstrated with much success. Many dry injection programs have used nahcolite as a sorbent. Nahcolite is a naturally occurring mineral, associated with western oil shale reserves, and is about 80 percent sodium bicarbonate. Sodium bicarbonate appears to be more reactive than sodium carbonate, because it loses both two moles of CO_2 and one of water in reaction, while sodium carbonate loses only one mole of CO_2 in reaction with SO_2. The following overall reactions illustrate this point:

$$2NaHCO_3 + SO_2 \qquad Na_2SO_3 + H_2O \qquad (1-1)$$

$$Na_2CO_3 + SO_2 \qquad Na_2SO_3 + CO_2 \qquad (1-2)$$

Since bicarbonate loses three moles for every mole of SO_2 removal, bicarbonate particles tend to have larger pore volumes and are apparently less susceptible to blinding on reaction than are sodium carbonate particles. Unfortunately, the availability of raw nahcolite in commercial quantities in the near future is questionable due to the substantial investment necessary before commercial scale mining can begin. Since the potentially favorable economics of dry injection are based to some extent on the use of inexpensive sorbents, the use of commercially refined sodium bicarbonate is prohibitively expensive. Recent research has been aimed at studying the use of raw trona ore, which is currently mined in large quantities both in the Green River, Wyoming area and the Owens Lake, California area. The mineral trona contains one mole of sodium carbonate, one mole of sodium bicarbonate and two waters of hydration ($Na_2CO_3 \cdot NaHCO_3 \cdot 2H_2O$). Trona has the potential for providing a good compromise between reactivity, cost, and availability for use in dry injection schemes.

An unresolved problem with this technology is disposal of the sodium-based waste materials in an environmentally acceptable manner. As mentioned previously, sodium waste materials are highly soluble and can result in contamination of aqueous streams. Disposal of sodium compounds is an area requiring further investigation.

Both baghouse and ESP collection devices have been tested with dry injection processes. However, the effect of the reaction between unspent sorbent on collecting bag surfaces and SO_2 remaining in the flue gas seems to overwhelmingly favor the bag collector (Ref. 15). Since a major portion of the SO_2 removal reaction appears to take place on the bag surface, various methods of feeding have been tested:

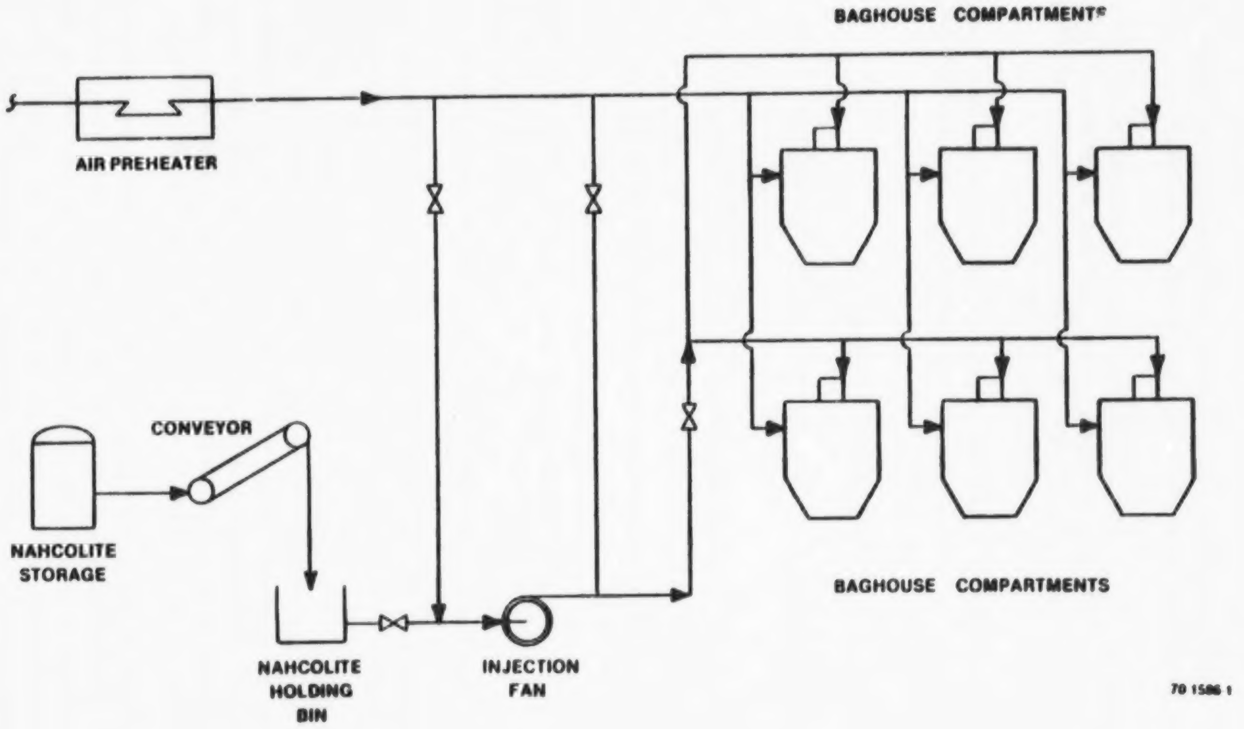
BAGHOUSE COMPARTMENTS
AIR PREHEATER
CONVEYOR
NAHCOLITE STORAGE
NAHCOLITE HOLDING BIN
INJECTION FAN
BAGHOUSE COMPARTMENTS
70 1586 1

Figure 2-2. Nahcolite dry injection flow diagram.

1) Continuous. After the bag is cleaned, sorbent entrained with the flue gas is added to the bag surface continuously from injection points located upstream of the baghouse.

2) Batch. After the bag is cleaned, all sorbent is added to the bag as a precoat before flue gas flow is resumed.

3) Semi-batch. This feeding method is a compromise between types 1 and 2. After bag cleaning some sorbent is added initially as a precoat and the remainder is added continuously throughout the bag cycle from an upstream injection point.

Sorbent stoichiometry, sorbent particle size, point and temperature of injection, baghouse air-to-cloth ratio, and bag cleaning frequency, are also varied in dry injection programs.

2.1.3 Combustion of Coal/Limestone Fuel Mixture

The current research on combustion of a coal/limestone fuel mixture has taken two forms:

1) Combustion of a coal/limestone pellet in an industrial spreader-stoker boiler.

2) Combustion of a pulverized coal/limestone mixture in a low-NO_x burner system.

Preliminary results of bench-scale test work on both processes have indicated that up to 80% of the available sulfur in the fuel can be retained by the limestone. The ratio of calcium to sulfur in the coal/limestone fuel mixture is important in determining how much sulfur is retained.

A spreader-stoker boiler (20bhp) has been used in testing the combustion and sulfur retention characteristics of the coal/limestone pellet. A Ca:S mole ration of 7:1 has been used so far, but further work with a 3:1 Ca:S pellet is planned. The emissions generated are dependent upon burner design, coal properties and combustion operating parameters. The inherent staged combustion of the stoker-fired boiler (accomplished by supplying the total combustion air as primary air through the grates and secondary air through over-fire jets above the bed) results in lower NO_x emissions relative to conventional pulverized coal-fired boilers.

The two-staged combustion concept was employed by Babcock & Wilcox (B&W) to design an advanced low-NO_x burner system. EPA has funded test work to develop a concept of firing a coal/limestone fuel mixture in B&W low-NO_x burners to reduce SO_2 emissions. Tests conducted on a 12 x 10^6 BTU/hr unit by the Energy and Environmental Research Corporatio (EERC), with a Utah low sulfur coal, have demonstrated 88 percent SO_2 removal with a 3:1 Ca:S mole ratio. This high SO_2 removal has been attributed to the lower flame temperature found in the low-NO_x burner which may help maintain limestone reactivity. EERC has reported that SO_2 removal increased substantially when the reagent was passed through the pulverizer with the coal.

Further research on a larger scale for both systems is needed to determine the effects of combustion of a coal/limestone fuel mixture on boiler operation and maintenance. Collection of the increased ash loading and investigation of the properties and disposal of the waste products must also be studied.

2.2 COMPARISON OF DRY AND WET SCRUBBING FOR SO_2 REMOVAL

Comparisons between dry and wet scrubbing systems can be drawn in five major areas: waste disposal, reagent requirements, operation and maintenance, energy requirements, and economics. This comparison will focus on general aspects of dry FGD systems as compared to conventional lime/limestone wet scrubbing systems.

With regard to waste disposal, dry FGD systems have an inherent advantage over wet lime/limestone systems in that they produce a dry, solid waste product that can be handled by conventional fly ash handling systems, eliminating requirements for a sludge handling system. However, the waste solids from sodium-based dry FGD systems are quite water soluble and can lead to leachability and waste stability problems. Waste solids from lime spray drying systems and coal/limestone fuel systems should have similar environmental impacts as waste from lime/limestone wet systems, for which waste disposal technology is better defined.

In general, dry FGD systems require a higher stoichiometric ratio of sorbent to entering SO_2 to achieve the desired removal efficiency than do conventional limestone wet scrubbing systems. In addition, the reagents employed in spray drying and dry injection systems (soda ash, lime, commercial and naturally occurring sodium carbonates and bicarbonates, such as nahcolite and trona) are significantly more expensive than limestone. Consequently, limestone wet scrubbing systems will have an advantage with regard to reagent utilization and sorbent-related operating costs.

It has been claimed that dry system will have lower maintenance requirements than comparable wet systems. Dry systems require less equipment than wet systems as the thickeners, centrifuges, vacuum filters and mixers required to handle the wet sludge waste product from wet systems are eliminated. In addition, slurry pumping requirements are much lower for spray drying and are eliminated in dry injection and combustion of coal/limestone fuel systems. This is important because wet systems have reported high maintenance requirements associated with large slurry circulation equipment. Finally, the scaling potential in limestone wet systems requires extra effort to maintain proper scrubber operation and possibly makes dry systems somewhat more flexible as far as their ability to adjust process operations to respond to variations in inlet SO_2 concentrations and flue gas flow rates.

With regard to energy requirements, dry FGD systems appear to have a significant advantage over wet systems due to savings in reheat and pumping requirements. Many wet FGD systems reheat the flue gas before it enters any downstream equipment to prevent corrosion. This reheat requirement is eliminated in most dry system configurations and results in considerable energy savings. Spray dryer systems are usually designed with a 30° to 50°F approach to the adiabatic saturation temperature of the flue gas at the outlet of the spray dryer. Energy savings from reduced pumping requirements result from the fact that wet scrubbers may require liquid to gas (L/G) pumping rates of up to 100 gallons per 1000 acfm of gas whereas spray dryers only require an L/G rate of 0.2 to 0.3.

One of the major driving forces for development of dry SO_2 removal systems is the opportunity for reduction in both capital and operating costs. Although costs are quite site specific, the three types of dry FGD technologies considered here offer several potential possibilities for cost savings. This is due to the reduction in equipment and operation and maintenance requirements relative to conventional wet lime/limestone systems, especially in utility applications. Basin Electric evaluated the costs of the two spray drying systems they have purchased (Antelope Valley and Laramie River Stations) to be about 20 to 30% less costly over the 35-year life of the plant than comparable wet systems (See Section 5.12). However, it should also be noted that these economics are based on pilot scale data and should be better determined after the operation of commercial systems has begun. Reagent costs for sodium-based spray dryer systems will be considerably higher than for lime-based systems although vendors claim the capital costs, excluding waste disposal, will be lower for sodium-based systems. The minimal equipment and operating requirements for dry injection systems make the process economically attractive as far as capital costs are concerned, but high sorbent requirements and uncertainties in sorbent availability and cost are slowing further development of the technology on a commercial scale. Capital costs for both the pellet and low-NO_x burner coal/limestone fuel mixture systems should also be low since they will consist mainly of the equipment needed to produce the mixtures. However, since these systems have the potential for impacting the design and/or operation of the boiler, more information on the overall operability of these systems is needed before overall operating costs can be estimated.

In summary, dry systems do offer potential advantages over wet systems, especially in the areas of energy savings and costs. However, crucial issues such as waste disposal and demonstration of commercial-scale systems, which may continue to limit the overall acceptability of this technology, remain to be answered.

SECTION 3

CONCLUSIONS AND RECOMMENDATIONS

The primary intent of this report is to describe the status of the development and commercial application of dry FGD in the United States, in both utility and industrial applications. However, after reviewing the current status of dry FGD, the following conclusions and recommendations have been made concerning the role EPA could assume to advance the acceptance and application of dry FGD technologies as a viable alternative for controlling SO_2 emissions. Because the three types of dry FGD technologies considered here are in quite different stages of development, the conclusions and recommendations are necessarily technology specific. Section 3.1 dicusses spray drying/particulate collection, Section 3.2 discusses dry injection/particulate collection, and Section 3.3 discusses combustion of pulverized coal/limestone fuel mixtures in low-NO_x staged combustion systems and pelletized coal/limestone mixtures in stoker-fired boilers.

3.1 SPRAY DRYING/PARTICULATE COLLECTION

With regard to process development, there does not appear to be a need for EPA to fund programs aimed at the development of spray-dryer based technology since a significant amount of commercial interest currently exists in these systems. Three Western utilities and two industrial FGD spray dryer systems are under construction and reportedly as many as six more utility applications will consider dry systems by the end of 1979. Consequently, numerous vendors of dry processes are devoting large research budgets to the development of spray dryer-based FGD systems, and it appears that this technology will be developed regardless of EPA involvement. However, the potential does exist for EPA to assist in helping prospective FGD users to better evaluate this technology by funding development programs to evaluate dry FGD overall environmental acceptability and to answer several unresolved technical questions. Recommendations on the direction of these development programs in four specific areas are discussed below.

1) Answer Unresolved Technical Questions

Waste Disposal-- One major unresolved technical issue is that of dry waste disposal, especially for sodium-based systems. The production of a dry waste rather than a sludge for disposal is seen as a major advantage of the dry systems over wet systems. However, no major development program has been aimed at optimizing disposal techniques for either sodium-based or calcium-based scrubber waste/fly ash mixtures. Although waste disposal is not seen as a technology limiting area, many unknowns such as water consumption rates, waste stability, load bearing qualities, and leachability have not been quantified.

Reaction Mechanism--Another key technical issue is that of defining the reaction mechanisms for SO_2 removal in the spray dryer. Until the reaction mechanisms are well understood, methods of improving spray dryer performance and expanding applicability can only be determined by an empirical approach. If the reaction mechanisms are well understood, the methods for improving spray dryer performance and the limits of spray dryer applicability will be better defined.

High Sulfur Coal Applications--As discussed previously in this section, most current spray dryer development work applies to low sulfur coals. An EPA-funded program to test this technology on higher sulfur coals could promote application of spray dryer technology for Eastern installations. Of course, such a program would be supported by a better understanding of the mechanisms of the SO_2 removal reactions in the spray dryer, as discussed above.

Limestone reagent investigations--The application of spray dryer technology to higher sulfur coals may be subject more to economic rather than technological limitations. Wet FGD systems can use limestone as a reagent, while spray dryer based systems are currently limited to the use of a more expensive lime reagent.

For high sulfur applications, where the reagent quantities involved tend to be large, the reagent cost differential between lime and limestone alone may make a spray dryer-based system uneconomical. Emphasis should be placed on the development of an effective spray dryer process using limestone as a reagent which would greatly improve these economics.

2) Demonstration of Technology

Of the three utility spray dryer-based FGD systems sold to date, the earliest commercial operation is slated for start up in mid-1981. The first industrial spray dryer based FGD system is scheduled for startup in late 1979. While these industrial applications should begin to demonstrate the operability and reliability of spray dryer-based systems almost immediately, these results may only be available to the process vendors and industrial clients involved. EPA funding of a commercial industrial or demo-scale utility spray dryer-based dry FGD system prior to the 1981 startup of the first utility system could provide data for evaluation of this concept by the utility industry as a whole.

3.2 DRY INJECTION/PARTICULATE COLLECTION

There is a significant data base for dry injection technology that indicates its technical feasibility as an SO_2 control alternative. Major restraints to development of commercial systems have been uncertainty in sorbent (nahcolite) availability, and uncertainty regarding acceptable disposal practices for the sodium-based waste material. EPA could help to these questions by funding programs to quantitatively answer both of these questions.

3.3 COMBUSTION OF LIMESTONE/COAL FUEL MIXTURES

To date only preliminary data exist for the SO_2 control effectiveness and operation of boilers firing either coal/limestone pellets or a pulverized coal/limestone fuel mixture. It is recommended that EPA continue to fund development programs in both of these areas with emphasis on validating the technology, determining the effects on boiler operation and maintenance, and ascertaining costs as a function of SO_2 removal.

SECTION 4

DRY FGD RESEARCH REVIEW

This section provides a summary of past research conducted on dry FGD methods. The research activities have been divided into three areas: 1) dry injection/particulate collection systems (4.1), 2) spray drying/particulate collection systems (4.2), and 3) other research including combustion of a coal/limestone fuel mixture and fixed and fluidized bed reactors (4.3). Table 4-1 presents a summary and brief description of the research activities reviewed in this section.

The research activities in each area are listed in chronological order as reported. The reviews cover the following areas:

- scope of the project,
- process description,
- parameters investigated,
- test conditions,
- conclusions and comments, and
- references.

For those activities where only limited information is available, the review covers only those entries in the above list which are applicable.

The results of previous test work have generally been published and are available in great detail. Results from current research activities are often not readily available because test work may not be completed, conclusions may not have been finalized, etc. Since it was the intent of this document to report as much information regarding dry FGD research as was available, the results of older, completed studies presented here are generally more complete and detailed than those of current or recent studies. It was not intended, however, to bias the content of the report toward earlier studies. Unfortunately, although the more recent studies are discussed in less detail, these are probably most indicative of the state of the art of dry FGD. Hopefully in future quarterly updates, more details of the current and recent research efforts will be available for presentation.

TABLE 4-1. LISTING OF RESEARCH ACTIVITIES CONDUCTED PRIOR TO APRIL 1979

TEST CONDUCTED BY	SYSTEM/SCALE	LOCATION/YEAR	FUNDING	SECTION	SORBENTS TESTED	INLET SO_2/INLET GAS TEMPERATURE	SIGNIFICANT RESULTS
Owens-Corning Fiberglass	Dry injection/fabric filter; bench-scale laboratory tests.	OCF facility; August 1970	National Air Pollution Control Administration (now EPA)	4.1.1	Slaked lime, slaked dolomite, nahcolite (high temperature testing for lime and dolomite)	2800 ppm/ 300° to 500° F and 800° to 900° F	Slaked lime and dolomite achieved 70 to 80% SO_2 removal at 800°F but with low (25 to 40%) additive utilization. Removal of SO_2 using nahcolite was about 60% with 75 to 83% additive utilization at 300°F.
Air Preheater Corp.	Dry injection/fabric filter; pilot-scale	Mercer Station (Public Service Electric and Gas Company); March 1971	NAPCA (now EPA)	4.1.2	Sodium bicarbonate, nahcolite hydrated dolomite, hydrated lime	Not Reported/ 270°F and 600°F	40% SO_2 removal with $NaHCO_3$; 16% utilization (at 270°F). 63% SO_2 removal with nahcolite; 63% utilization (at 350°F). 20% SO_2 removal with dolomite; 7% utilization (at 350°F).
Wheelabrator-Frye, Inc.	Dry injection/fabric filter, pilot-scale	Nucla Station (Colorado Utility Electric Assoc.); July 1974	—	4.1.3	Nahcolite	About 600 ppm (0.8% S coal) Some tests with 900 ppm (1.1% S) 285°F	70% SO_2 removal achieved, 60% additive utilization.
American Air Filter	Dry injection/fabric filter; laboratory and bench-scale	AAF Labs; 1976	Arizona Public Service	4.1.4	Nahcolite and trona	450 to 600 ppm 200° to 250 °F	Up to 90% SO_2 removal with a stoichiometric ratio (SR) of 2.3 moles Na_2CO_3/mole S fed at 250°F. Moisture content of at least 5% required for effective SO_2 removal. Up to 70% removal using trona, (SR = 1.9).
Wheelabrator-Frye, Inc.	Dry injection/fabric filter; pilot-scale	Leland Olds Station (Basin Electric) March 1977	—	4.1.5	Nahcolite	850 to 1000 ppm (Some tests up to 2700 ppm) 285 to 300°F	90% SO_2 removal with SR of 1.6 (56% utilization) under optimum conditions. 99% particulate collection.
Grand Forks Energy Development Center/DOE	Dry injection/ESP and Dry injection/fabric filter; bench-scale	GFETC Labs/1975	Dept. of Energy (DOE)	4.1.6	Nahcolite and trona	Not reported/ Not reported	Dry injection/ESP found unsuitable with respect to SO_2 removal capabilities. 90% removal efficiencies on a baghouse with 30 to 60% additive utilization at air to cloth ratios of 3.
KVB, Inc.	Dry injection/fabric filter; bench-scale	KVB Labs; 1977 to 1979.	Electric Power Research Inst. (EPRI)	4.1.7	Commercial sodium bicarbonate, nahcolite, trona, soda ash solution, predecomposed nahcolite.	250 to 750 ppm/300 to 800° F or 230° to 320°F	Will be discussed in EPRI final report in late 1979.
Carborundum	Dry injection/fabric filter on stoker-fired boiler; pilot-scale	Industrial stoker boiler; 1976	—	4.1.8	Sodium bicarbonate, nahcolite, ammonia.	Not reported	Report not released.

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(continued)

TABLE 4-1. (continued)

TESTS CONDUCTED BY	SYSTEM/SCALE	LOCATION/YEAR	FUNDING	SECTION	SORBENTS TESTED	INLET SO_2/INLET GAS TEMPERATURE	SIGNIFICANT RESULTS
Atomics International (Division of Rockwell, Inc.)	Spray dryer/ESP; pilot-scale	Mohave Station (Southern Calif. Edison); 1977	WEST Assoc. of Utilities	4.2.1	Sodium Carbonate	Usually 400 ppm Concentrations up to 1663 ppm used in "high" SO_2 testing/250° to 340°F	90% SO_2 removal efficiency under optimum conditions. Additive utilization approached 90%.
Bayo Iron Works (Japan)	Spray dryer/ESP; pilot-scale	Bayo facility; 1973	—	4.2.2	Sodium hydroxide and sodium carbonate	600 to 1700 ppm/ 320° to 410°F	89% SO_2 removal with stoichiometric ratio of 1.2 (1700 ppm SO_2 inlet) with NaOH solution. Removal varied between 70 and 90% depending on stoichiometric ratio, inlet and outlet gas temperatures.
Rockwell (Atomics Int. Division)/Wheelabrator-Frye	Spray dry/baghouse; pilot-scale	Hoot Lake Station (Otter Tail Power Co.); 1977-1978	—	4.2.3	Sodium carbonate, trona hydrated lime/limestone	670 to 2070 ppm/ 250° to 330°F	With sodium carbonate and trona up to 85% of inlet SO_2 was removed across spray dryer with an additional 10 to 20% across the baghouse. Sorbent utilization ranged from 80 to 100%. 45 to 60% SO_2 removal with low additive utilization with lime on a once through basis (no recycle of product solids.
Joy Manufacturing (Western Precipitation Division)/ Niro Atomizer, Inc.	Spray dryer/baghouse; pilot-scale.	Hoot Lake Station (Otter Tail Power Co.), 1977-1978	—	4.2.4	Lime and soda ash	200 to 2000 ppm/ 310°F	About 83% SO_2 removal achieved with near theoretical amounts of lime when partial recycle of solids employed. 90% removal achieved with near theoretical amounts of lime without recycle.
Babcock and Wilcox	Spray dryer/ESP; pilot-scale	Neal Station (Basin Electric); 1978	—	4.2.5	Soda ash, pebble lime, hydrated lime, ammonia addition with lime and precipitated limestone.	Not reported/NR	Report not released.
Carborundum/DeLaval	Spray dryer/baghouse, pilot scale	Leland Olds (Basin Electric); 1978	—	4.2.6	Lime, soda ash, ammonia	Not reported/NR	Report not released.
FMC Corporation	Fixed bed reactor; bench scale	FMC labs; 1969-1970	NAPCA (now EPA)	4.3.1	Sodium carbonates, impregnated silica gels, fly ash, hydroxides, and sulfides	3300 ppm/260°F	Sodium carbonates considerably more reactive than any other materials tested.
Nagoya Institute of Technology	Multi-stage bed reactor	Nagoya labs; 1973	—	4.3.2	Soda ash	1050 to 3460 ppm (in air)/300, 400 480 and 570°F	Removals of 97+% achieved under most conditions.
Stearns-Roger/Superior Oil	Fixed-bed bench scale to investigate reaction kinetics; pilot-scale countercurrent reactor	1974	—	4.3.3	Sodium bicarbonate, nahcolite	800 and 2420 ppm/ 280° to 300° F	80 to 84% SO_2 removal with sodium bicarbonate with 90% additive utilization. 67% removal and 73% additive utilization in nahcolite run. High pressure drop. (Results are for countercurrent reactor)
B.W.B. Tests in Germany	Combustion of pulverized coal/limestone fuel mixture in low NO_x burner; 60 MW	1978 to Present	—	4.3.4	Limestone	0.4 to 0.72% S Coal	60 to 90% SO_2 removals with Ca:S ratio of 3 with coal of 0.4 to 0.72% S.

4.1 DRY INJECTION/PARTICULATE COLLECTION

4.1.1 Owens-Corning Fiberglass, Laboratory Tests, August 1970

Scope

In an effort to develop fabric filters that would withstand high temperatures, Owens-Corning Fiberglass (OCF) developed an S-glass cloth treated with a proprietary inorganic finish. Under contract with the National Air Pollution Control Administration, now EPA, a stainless steel test facility to assess the filtration and contacting characteristics of the new fabric was constructed and operated during 1970. The emphasis was on investigating various sorbents for SO_2 removal from flue gas at high temperatures.

Process Description

The test facility was a single compartment stainless steel baghouse with 6 bags. Two methods of sorbent feeding were tested: 1) continuous injection of the dry sorbent into the simulated flue gas, upstream of the baghouse and 2) pre-coating of the bag by injecting the sorbent into SO_2-free gas to build up a dust cake on the bag before the regular gas stream (containing SO_2) was started.

The synthetic flue gas was supplied by a natural gas boiler-heat exchanger and spiked with SO_2. Hot and warm flue gas streams were controlled to give a gas temperature between 250 and 1000°F at varying flow rates and constant composition.

Bag cleaning was accomplished by conventional reverse-air shaking methods. Inlet and outlet SO_2 concentrations, pressure drop across the bags, and baghouse temperatures were continuously monitored.

Parameters Investigated

The tests were divided into four series: an additive study, a flue gas flow rate study, a precoated bag study, and a fly ash study. Parameters investigated within these series included:

- type of sorbent,
- gas stream temperature,
- flue gas flow rate,
- stoichiometric ratio, and
- additive feeding method.

Test Conditions

Inlet SO_2 concentration was maintained at 2800 ppm. The test cyle was usually 60 minutes. The average flue gas composition was 3.5 percent H_2O, 81.0 percent N_2, 5.6 percent O_2, 1.0 percent Ar, and 9.0 percent CO_2. See Table 4-2 for a summary of the variable test conditions.

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TABLE 4-2 VARIABLE TEST CONDITIONS - OCF LABORATORY TESTING[21]

Series	Feed Method[a]	Sorbent	Stoichiometric Ratio	Temp. Range	Flue Gas Flow
Additive Study	1 in all cases	slaked lime	1.0-3.0	700-900°F	290 cfm in all cases air-cloth ratio = 6.0ft/min
		promoted (1% NaCl) slaked lime	1.0-3.0	700-900°F	
		slaked dolomite	1.0-3.0	700-900°F	
		promoted (1% NaCl) slaked dolomite	1.0-3.0	700-900°F	
		MnO_2	1.0-3.0	500-700°F	
		nahcolite	1.0	300-500°F	
		alkalized alumina	1.0	300-500°F	
Flue Gas Flow Rate Study	1 in all cases	same as above	same as above	same as above	385 cfm (A/C ≅ 80 ft/min) (except nahcolite which was 685 cfm)
Fly Ash Study	1 in all cases	slaked lime	NR	800°F	385 cfm for all cases
		promoted slaked lime	NR	800°F	
		slaked dolomite	NR	800°F	
		promoted slaked dolomite	NR	800°F	
		MnO_2	NR	800°F	
	2 in all cases	slaked lime	1.0-3.0 for all cases	700-900°F	290 and 385 cfm for each case
		promoted slaked lime		700-900°F	
		slaked dolomite		700-900°F	
		promoted slaked dolomite		700-900°F	
		MnO_2		300-500°F	

[a] 1 - continuous feed to flue gas flow; 2 = pre-coat of bags.

NR = not reported.

Results

The percentage SO_2 removal was calculated using conventional breakthrough curves. Some of the results for runs with continuous injection of sorbent are summarized in Table 4-3.

Slaked lime and dolomite achieved maximum SO_2 removals at 800°F. However, additive utilization was low, with a value of only 40 percent at 81 percent SO_2 removal.

Promoted slaked limes did not perform significantly better than slaked limes. Both MnO_2 and alkalized alumina gave good SO_2 removals (70 percent for MnO_2 and 70 to 90 percent for alkalized alumina depending on test conditions). Again, additive utilization was low and a regenerative process would definitely be required for these expensive sorbents.

Increasing turbulence by increasing the flue gas flow rate improved SO_2 removal and additive utilization when lime sorbents were used. This indicates that lime sorption of SO_2 may be gas-phase mass transfer limited at the high temperatures used in these tests.

In the tests using nahcolite sorbent, an increase in flow rate did not enhance SO_2 removal, but it did improve additive utilization. Overall, nahcolite utilization was greater than lime utilization 75 percent versus 40 percent at 290 cfm.

Precoating of the bags was not an effective method of removing SO_2 when lime sorbents were used. This was attributed to the absorption of the CO_2 present in the SO_2-free flue gas used in coating the bags, thus reducing the amount of lime available to react with the SO_2.

Fly ash addition did not affect SO_2 removals.

Conclusions and Comments

Slaked lime and dolomite achieved satisfactory SO_2 removals at 800°F but with low reagent utilization. These high temperatures are not likely to be encountered in commercial dry injection FGD systems, as the hot flue gas passes through an air preheater upstream of the injection point and/or fabric filter.

Removal of SO_2 using nahcolite was about 60 percent with 75 to 85 percent additive utilization at 300°F (the inlet SO_2 concentration was 2800 ppm). Also, the dry product formed is quite water soluble and waste disposal problems may occur.

Information Sources

Veazie, F. M., and W. H. Kielmeyer, "Feasibility of Fabric Filter as Gas-Solid Contactor to Control Gaseous Pollutants". Report No. APTD-0595 for the National Air Pollution Control Administration, HEW Contract No. Ph-22-68-64, Owens-Corning Fiberglass Corporation, Granville, OH. August 1970.

TABLE 4-3. PERCENTAGE SO_2 REMOVAL WITH CONTINUOUS SORBENT INJECTION - OCF LABORATORY TESTS[21]

Reactant: Slaked Lime

Flow Rate:	290 cfm			385 cfm	
Stoichiometric Ratio:	1.0	2.0	3.0	2.0	3.0
Bag Temperature					
700°F	-	46%	64%	57%	74%
800°F	40%	65%	78%	81%	91%
900°F	-	52%	70%	65%	81%

Sorbent Utilization[a] :
maximum 40%
minimum 26%

Reactant: Slaked Dolomite

Flow Rate:	290 cfm			385 cfm	
Stoichiometric Ratio:	1.0	2.0	3.0	2.0	3.0
Bag Temperature					
700°F	-	40%	54%	40%	52%
800°F	30%	52%	64%	55%	70%
900°F	-	34%	49%	44%	60%

Sorbent Utilization[a]: 25%

Reactant: Nahcolite

Flow Rate:	290 cfm	385 cfm
Stoichiometric Ratio:	0.8	0.7
(Temp = 300°F)	59%	60%

Sorbent Utilization[a] :
75% @ 290 cfm
80% @ 685 cfm

---

[a] Sorbent Utilization = percent SO_2 removal/Stoichiometric Ratio

4.1.2 Air Preheater at Mercer Station, March 1971

Scope

The Air Preheater Corporation was contracted by the National Air Pollution Control Association (now EPA) to conduct tests to investigate the potential of the top inlet fabric filterhouse as a chemical contactor for SO_2 removal from flue gas. The study was carried out at a pilot test facility at the Mercer Station of Public Service Electric and Gas Company in Trenton, New Jersey during 1971.

Process Description

The filterhouse (baghouse) test facility of top entry design had four compartments, each containing nine fiberglass filter bags. The total filter area was 4300 ft^2. The bags were cleaned by the reverse-air deflation method. In addition, two different types of baghouse operation, cyclic and parallel, and both continuous and batch sorbent feeding methods were tested. Sorbent could be added upstream of the baghouse, just before the baghouse or precoated onto the fiter bags.

Flue gas was available at temperatures from 270°F (leaving the air preheater) to 680°F (just ahead of the air preheater) and was mixed to give a variety of operating temperatures. Inlet and outlet SO_2 concentrations, as well as temperatures and pressure drops, were continuously monitored.

Parameters Investigated

The study was performed in two phases. The first phase evaluated the feasibility of the process using sodium bicarbonate, $NaHCO_3$. The second phase investigated the process variables at higher temperatures using different sorbents (nahcolite, hydrated dolomite, promoted hydrated dolomite, and hydrated lime). The process variables investigated were:

- stoichiometric ratio,
- operating temperature,
- filter air-cloth ratio (flue gas flow),
- method of sorbent feeding, and
- mode of baghouse operation.

Test Conditions

Flue-gas flow rates of 7,500, 10,000 or 15,000 acfm were used to give corresponding air-to-cloth filter ratios of 1.75, 2.3, or 3.5, respectively. The flue gas temperatures ranged from 270 to 650°F. No SO_2 inlet concentrations were reported. The moisture level was given as 5 percent. The tests were usually conducted in 40-minute cycles.

Results

About half of the total 62 tests were run with sodium bicarbonate at various operating conditions. Increasing the stoichiometric ratio increased

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the SO_2 removal with accompanying decreased sorbent utilization. An increase in operating temperature also increased SO_2 removal. Table 4-4 provides a summary of the tests results with $NaHCO_3$, nahcolite, and hydrated dolomite, although the results are of limited value without inlet SO_2 concentrations.

TABLE 4-4. SUMMARY OF AVERAGE SO_2 REMOVAL AND SORBENT UTILIZATION AIR PREHEATER CORP. AT MERCER STATION [14]

Additive	Temp. (°F)	Stoichiometric Ratio = 1		Stoichiometric Ratio = 3	
		Conv. Efficiency	Additive Utilization	Conv. Efficiency	Additive Utilization
Sodium Bicarbonate	270	32%	32%	48%	16%
Sodium Bicarbonate	350	48%	48%	76%	26%
Sodium Bicarbonate	600	90%	90%	-	-
Nahcolite	350	65%	65%	85%	30%
Nahcolite	600	94%	94%	-	-
Dolomite	350	-	-	20%	7%
Dolomite	600	20%	20%	38%	13%

Nahcolite tests results showed trends similar to those in sodium bicarbonate tests. Nahcolite gave a somewhat higher SO_2 removal than sodium bicarbonate at the same temperature and stoichiome-ric ratio. The investigators claim this may have been due to the smaller particle size of the nahcolite. Sulfur dioxide removal efficiencies were low in tests with lime at 350°F.

As to the variation with mode of baghouse operation, parallel operation resulted in higher removals for continuous additive feeding. This seems to be a result of the lower air-to-cloth ratio of parallel operation, where all the compartments are on-stream during the cycle, as compared to the higher ratio resulting when one of the compartments is always off-stream for cleaning during cyclic operation. This is in agreement with results of tests with increased air-to-cloth ratios that show a decrease in SO_2 removal and additive utilization for both $NaHCO_3$ and nahcolite at temperatures from 280° to 350°F. When lime was used, the removal efficiency and additive utilization increased with higher flue gas flow rates.

Data from the chemical analyses of fallout and shakedown samples were used to approximate the conversion distribution in the filterhouse. Although only approximations could be made, it appeared that most of the conversion, up to 80%, occurred in the filter cake for tests with sodium bicarbonate and nahcolite at 350°F. However, for lime the bulk of the conversion was in the gas suspension. These calculations were based on the assumption that no chemical reaction took place in the fallout collected from the hopper.

Conclusions and Comments

The use of a fabric filter as a chemical contactor to remove SO_2 through reaction with a dry sorbent was proven feasible. The additive utilization was fairly low at flue gas temperatures below 350°F. Higher temperatures (650°F) are required for lime to be an effective sorbent.

Stoichiometric ratio and operating temperature appear to have the strongest effect on SO_2 removal. The inlet SO_2 concentration was not specified for any of the tests. The moisture content (5 percent) of the flue gas was somewhat lower than most of the other similar studies on the dry injection/baghouse process.

In tests with nahcolite and sodium bicarbonate at flue gas temperatures of about 300°F, the effect of increasing flue gas flow was small. This suggests that the reaction is not gas-phase mass transfer limited at these temperatures. However, in tests with lime at 650°F, the increase in flue gas flow rate substantially increased the SO_2 removal efficiency, indicating that this reaction may be gas-phase mass transfer limited at higher temperatures.

Information Sources

Liu, Han and R. Chafee, "Evaluation of Fabric Filter as a Chemical Contactor for Control of SO_2 in Flue Gas," presented at the Air Pollution Control Office Fabric Filter Symposium, Charleston, S.C. March 1971.

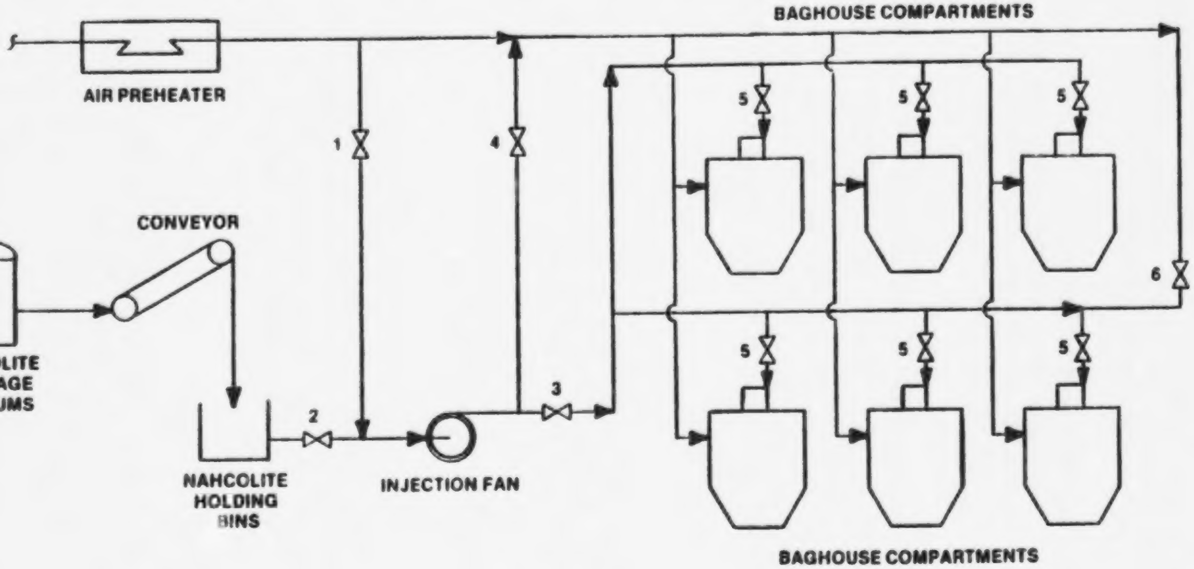
4.1.3 Wheelabrator-Frye at Nucla Station, July 1974

Scope

In July 1974 Wheelabrator-Frye conducted tests at the Nucla Station of the Colorado Ute Electric Association. The tests were performed to demonstrate the applicability of dry nahcolite injection into a commercially available baghouse to remove SO_2 from the flue gas.

Process Description

The tests were conducted on a unit comprised of an 11 MW spreader-stoker-fired boiler burning low sulfur coal and a Wheelabrator-Frye continuous automatic fabric filter collector. Figure 4-1 shows the schematic process flow diagram. Fifteen of sixteen tests were conducted in a batch feeding mode. The most frequently employed procedure was to inject all the nahcolite at the beginning of the test cycle by blowing it into the bags through a common inlet manifold using the injection fan. In some runs the nahcolite was injected into a single compartment, in which case the injection fan was used to overcome the added pressure drop that resulted across that compartment.


BAGHOUSE COMPARTMENTS
AIR PREHEATER
1
4
5
5
5
CONVEYOR
6
NACHOLITE STORAGE IN DRUMS
5
5
5
3
2
NAHCOLITE HOLDING BINS
INJECTION FAN
BAGHOUSE COMPARTMENTS

FUNCTION	VALVE NO. 1	2	3	4	5*	6
• NO NACHOLITE INJECTION	X	X	X	X	X	X
• NACHOLITE FEED TO COMMON INLET	O	O	X	O	X	X
• NACHOLITE FEED TO INDIVIDUAL COMPARTMENTS	O	O	O	X	O	X
• PURGE SYSTEM OF NACHOLITE	O	X	O	X	X	O

·VALVE OPERATION: O = OPEN
X = CLOSE

VALVE NO.	TYPE
1	BUTTERFLY-MANUAL OPERATED
2	ROTARY-ELECTRIC MOTOR OPERATED
3	BUTTERFLY-MANUAL
4	BUTTERFLY-MANUAL
5	BUTTERFLY-SOLENOID
6	BUTTERFLY-SOLENOID

*ONLY ONE NO.5 VALVE CAN OPEN AT A TIME.

Figure 4-1. Process Schematic - gas and nahcolite into baghouse. Wheelabrator-Frye at Nucla Station.[16]

70-1593 1

The filter bags were of silicone-graphite-treated fiberglass and were cleaned by reverse air-shaking methods.

The SO_2 inlet and outlet gas concentrations were monitored continuously.

Parameters Investigated .

The primary parameters investigated for their effects on SO_2 removal and additive utilization are listed below:

- SO_2 inlet concentration,
- method of additive feeding,
- stoichiometric ratio,
- air-to-cloth ratio, and
- cycle time between bag cleaning.

Test Conditions

Most of the tests were conducted with 0.8 percent S coal, resulting in a 480 ppm inlet SO_2 concentration. When a higher sulfur coal (1.1 percent S) was burned, the SO_2 inlet concentration was around 900 ppm. The flue gas flow to the baghouse was 32,000 scfm at a temperature of 285°F (44,000 acfm). The stoichiometric ratios tested ranged from 0.2 to 3.4. he nahcolite was 60 percent $NaHCO_3$. Flue gas composition was not given.

Results

Sulfur dioxide removal efficiencies for 90-minute cycles varied from 50 to 70 percent. The additive utilization was 56 percent and 70 percent SO_2 removal. Pressure drop over the fabric filter ranged from 2 to 5 in. H_2O. A change in air-to-cloth ratio did not affect SO_2 removal.

Single compartment injection resulted in a slightly lower overall removal efficiency in a continuously operating system. This is due to the fact that the lower cake resistance encountered after bag cleaning results in lowered SO_2 removal.

Conclusions and Comments

This series of tests conducted by Wheelabrator-Frye demonstrated the feasibility of SO_2 removal by nahcolite injection into the baghouse. The fact that 70% SO_2 removal, with reasonable additive utilization, was achieved on a system with commercial hardware not specifically designed for optimum sorbent utilization is significant. The success of the tests at Nucla Station led to more demonstration work by Wheelabrator-Frye at Basin Electric's Leland Olds Station in early 1977.

Information Sources

Bechtel Corp., Evaluation of Dry Alkalis for Removing SO_2 from Boiler Flue Gases. EPRI Final Report FP-207, October 1976.

4.1.4 American Air Filter, Laboratory Tests, 1976

Scope

In 1972 American Air Filter, with substantial funding from Arizona Public Service, conducted bench-scale studies to investigate the use of fabric filters as chemical contactors for SO_2 removal from flue gas.

Process Description

Reactant and fly ash were introduced into synthetic flue gas flowing in a vertical tube 8.3" in diameter and 29.5" long. A filter made of commercial fiberglass bag fabric was clamped and sealed across the bottom of the tube. After investigating both batch and continuous modes of reactant/fly ash feeding and observing no difference in performance, most of the remaining tests were conducted using the easier-to-control continuous mode.

Parameters Investigated

Tests were conducted to evaluate the following parameters over the given ranges:

- sorbent type,
- flue gas velocity (2.0 to 4.4 ft/min),
- sorbent stoichiometric ratio (0.75 to 4.5),
- temperature (200 to 250°F),
- moisture content of flue gas (1.1 to 7.7%), and
- fly ash concentration (0.18 to 15.6 gr/ft^3).

The stoichiometric ratio was defined as moles of Na_2CO_3 feed per mole of S in the inlet flue gas stream.

Test Conditions

The primary sorbents investigated were nahcolite and trona ($Na_2CO_3 \cdot NaHCO_3 \cdot 2H_2O$). The SO_2 concentration ranged from 450 to 600 ppm. The flue gas averaged 1.5 percent O_2, 14 to 15 percent CO_2, and 76 to 82 percent N_2, depending on the moisture content.

Results

Removal efficiencies of up to 90 percent were achieved when the moisture content was greater than 5 percent. Removal decreased significantly below this moisture level, but little effect was observed upon increasing the moisture content above 5 percent. Increasing the stoichiometric ratio increased SO_2 removal. Higher operating temperatures resulted in better additive utilization as well as greater SO_2 removal. Fly ash content had no effect on performance. Table 4-5 provides a summary of results illustrating these trends. It is not clear on what basis additive utilizations were calculated.

TABLE 4-5. SUMMARY OF RESULTS OF NAHCOLITE AND TRONA TESTS - AMERICAN AIR FILTER[16]

Reactant	Inlet SO_2 Conc. (ppm/v)[a]	Temperature (°F)	Stoichiometric Ratio[b]	Water Vapor (mole %)	Air to Cloth Ratio	SO_2 Removal[c] (%)	Utilization (%)
Nahcolite	599	255	2.3	5.5	3.7	92	40
Nahcolite	478	248	1.15	7.4	4.0	65	56
Nahcolite	545	249	2.2	2.2	4.15	62	28
Nahcolite	544	251	2.2	6.3	3.95	87	40
Nahcolite	526	205	2.1	6.6	3.8	70	34
Nahcolite	547	254	1.9	5.7	3.9	87	46
Trona	540	250	1.9	8.6	4.1	71	38
Trona	551	250	1.2	7.8	4.1	51	42

[a] The SO_2 concentrations in Rivers, *et al* have been recalculated from a weight basis to a volume basis.

[b] Stoichiometric ratio is defined as moles Na_2CO_3 fed per mole S fed.

[c] After 60 minutes of operation.

In a test conducted without a filter essentially no SO_2 was removed. This indicated that reaction occurred primarily on the filter cake and not in the gas-solid suspension.

Conclusions and Comments

Both nahcolite and trona were shown to be effective SO_2 removal agents. Trona was found to be less reactive than nahcolite, but the authors suggested that reactivity could be improved by such means as particle size optimization.

A moisture content of at least 5 percent was required for effective SO_2 removal. Increases in moisture content above 5 percent did not significantly increase removal.

The observation that no reaction occurred in the gas-solid suspension may be explained in part by the laminar nature of flow in the test apparatus. Because the relative gas/particle velocity is small, a stagnant film of gas surrounds the particle and mass transfer can only take place by molecular diffusion (no convective diffusion by turbulence). This requires high bulk SO_2 concentrations to overcome film resistance.

Information Sources

Rivers, R.D., et al, "The Role of Fabric Collectors in Removing SO_2," presented at the 1st National Fabric Alternatives Forum, Denver, CO, July 1976.

4.1.5 Wheelabrator-Frye at Leland Olds, March 1977

Scope

Wheelabrator-Frye conducted pilot testing of a dry injection process using nahcolite for SO_2 removal with a baghouse collection device. The tests were carried out at Basin Electric's Leland Olds Station in Stanton, ND during the period of January through March 1977. Bechtel Power Corporation acting for the Otter Tail Power Company, coordinated the overall effort. The tests were performed to demonstrate the viability of the dry injection process for use at the full-scale Coyote Station being planned by Otter Tail Power Company. Process conditions at Leland Olds were similar to those expected at the new facility.

Process Description

Leland Olds Unit 2 is a 440 MW facility with a North Dakota lignite-fired boiler. The Wheelabrator-Frye process, based on test work at the Nucla Station in 1974, involved injecting dry nahcolite and collecting the solids with a baghouse filter. The SO_2 is removed through chemical reaction with the nahcolite. Several possible feeding procedures were considered: 1) feeding all of the nahcolite at the start of the cycle in the batch mode, 2) feeding nahcolite continuously throughout the cycle, and 3) combinations and variations of the two methods. Provisions were made for SO_2 spiking of the flue gas and for high temperature testing by injecting the nahcolite into hot flue gas upstream of the air preheater. The use of a booster fan to blow the gas that, depending on the feeding method, may or may not have contained SO_2, helped to disperse the nahcolite if it was present.

The Wheelabrator-Frye twelve-compartment baghouse contained fiberglass bags with a silicone-graphite finish that comprised a total filter area of 1080 ft^2. The cleaning of the filters was accomplished with conventional deflation-shaker methods.

Temperatures and SO_2 inlet and outlet concentrations were continuously monitored.

Parameters Investigated

The primary parameters investigated were nahcolite feeding method, stoichiometric ratio, and SO_2 inlet concentration. The effect of pretreating the nahcolite by heating to decompose $NaHCO_3$ to more porous Na_2CO_3 was also examined.

Test Conditions

The air-to-cloth ratio in the baghouse was 3:1 with the normal flue gas flow of 3100 acfm. The flue gas composition ranges were given as 10.5 to 15 percent CO_2, 77 to 83 percent N_2, and 5.5 to 8 percent O_2 on a dry basis with a moisture content of 13 to 16 percent. The stoichiometric ratio varied between 0.8 and 1.7. The SO_2 inlet concentration was usually between 850 and 1000 ppm with extremes of 830 and 2700 ppm SO_2. Baghouse temperatures ranged from 286 to 301°F.

Results

It was found that 90 percent SO_2 removal could be achieved at a stoichiometric ratio of 1.6 under optimum conditions. Variations in SO_2 inlet concentration appeared to have only a small effect on nahcolite performance with removal at higher concentrations being slightly better. Collection of filterable particulates was 99+ percent in all cases, and baghouse performance remained satisfactory even when large quantities of nahcolite were injected. It was also reported that feeding procedures had a significant effect on additive utilization. However, these effects were not detailed. No results of high temperature testing were given.

Conclusions and Comments

The pilot plant test work at Leland Olds by Wheelabrator-Frye appeared to show that substantial SO_2 removal by nahcolite injection is possible under optimum conditions. These "optimum" conditions were not specified in the available literature. However, additive utilization at 90 percent SO_2 removal is only about 56 percent, even under optimum conditions. The resulting large nahcolite requirements pose a serious problem due to great uncertainties in nahcolite availability (see Bechtel report listed below).

Although it was noted that nahcolite feeding procedures had a significant effect on additive utilization, these effects were not discussed nor was an optimum method of feeding given.

Information Sources

Bechtel Corp., Evaluation of Dry Alkalis for Removing SO_2 from Boiler Flue Gases, EPRI Final Report FP-207, October 1976.

Wheelabrator-Frye, Nahcolite Pilot Baghouse Study - Leland Olds Station, Non-Confidential Test Data, unpublished, March 1977.

4.1.6 Grand Forks Energy Development Center, DOE; Bench-scale Dry Injection/ESP or Baghouse Collection, 1975 to Present

Scope

DOE-Grand Forks dry FGD work began in 1975 during bench scale combustor/ESP testing of North Dakota lignite when sulfur retention was observed in fly ash alkalinity. The current dry FGD program was begun around the first of 1978, with the testing of nahcolite injection and ESP collection. The scope of the project was broadened to include Green River area trona as a sorbent. Later, when it was apparent that high SO_2 removal efficiencies were not demonstrable with this configuration, the ESP collector was replaced by a bag collector and testing was resumed.

Process Description

The Grand Forks bench scale coal combustor produces a nominal 200 scfm flue gas flow rate. Ductwork downstream of the combustor is equipped with water cooling so that the time/temperature profile of the flue gas can be varied. Injection points are also variable.

Parameters Investigated

The test program with a bag collector has so far included over 30 tests, where injection and bag temperatures, sequencing of sorbent addition and bag cleaning, bag materials, sorbent (nahcolite and trona), and bag air-to-cloth ratios were varied.

Results

The dry injection/ESP system was not effective for SO_2 removal. The dry injection/bag collector was much more suitable. SO_2 removal efficiencies on the order of 90 percent at 50 to 60 percent utilization were demonstrated at an air-to-cloth ratio of 3 ft/min. At higher air-to-cloth ratios (up to 6 ft/min), lower sorbent utilization resulted, as low as 10 to 30 percent. Current plans are to operate the dry injection/baghouse collection system another 6 months at various selected "optimum" conditions. Detailed results will be available when the final report for the study is published after this additional test period. Plans call for a final report around the end of 1979.

Grand Forks has also identified upcoming dry FGD related work. After the startup of the Coyote plant, in spring 1981, Grand Forks will sample the FGD system for particulate and SO_2 removal efficiencies.

Another upcoming program has actually begun, but very little progress has been made. This program involves column work and beaker tests with samples of spent sorbent and fly ash products from the Leland Olds dry FGD pilot operations. Initial studies involve leaching and solubility studies and toxicant extraction of the untreated wastes. Future studies may include similar testing of chemically fixed wastes.

Information Sources

Blythe, Gary. Telephone conversation with Stanley J. Selle, DOE, June 7, 1979.

Blythe, Gary. Telephone conversation with Harvey Ness, DOE, July 3, 1979.

4.1.7 KVB Incorporated, Bench Scale Tests, Late 1977 to Present

Scope

This bench scale study was funded by the Electric Power Research Institute, Inc. (EPRI) for the purpose of obtaining basic process data for a dry injection/baghouse collection FGD system. The test work was performed on KVB's bench-scale coal-fired combustor in Tustin, California. Six sodium-based sorbents were tested over a wide range of operating conditions.

Process Description

The source of flue gas for the test work was the coal-fired KVB bench scale combustor which produced a flue gas flow of approximately 725 scfm. A baghouse was installed downstream of the combustor for collecting fly ash and spent sorbent. A heat exchanger was installed in the duct between the combustor and baghouse in order to control the flue gas temperature at the baghouse inlet. The duct was designed for sorbent injection at several points between the boiler and baghouse, so that sorbent injection temperature and residence time in the duct could be varied.

Parameters Investigated

The sodium-based sorbents investigated in this extensive test program were:

1) commercial bicarbonate,
2) nahcolite,
3) Green River (Wyoming) trona,
4) Owens Lake (California) trona,
5) soda ash solution (sprayed into duct for evaporation), and
6) predecomposed nahcolite (heated to release CO_2 and water).

The following data summarizes the parameters and ranges investigated in this test program:

Stoichiometric ratio	0 to 4:1
Injection temperature	550 to 800°F upstream of heat exchanger 230 to 320°F at baghouse inlet

Particle size	35 to 400 mesh
Inlet SO_2 concentration	350 to 750 ppm
Baghouse air-to-cloth ratio	1 to 4 $\frac{ft^3/min}{ft^2}$
Sorbent feed method	Continuous Batch Semibatch (bag precoat)

Results

The final report of these results is due to be completed in late 1979. Since the reporting of the results is currently in draft form, EPRI was reluctant to discuss results in detail. However, the results were described as being generally very encouraging as to the future of dry injection as an FGD system.

Information Sources

Blythe, Gary. Telephone conversation with Navin Shah, EPRI Project Director, July 17, 1979.

Shah, N.D., et al., "Application of Dry Sorbent Injection for SO_2 and Particulate Removal," paper presented at the EPA Symposium on Flue Gas Desulfurization, Hollywood, Florida, November 11, 1977.

4.1.8 Carborundum, Dry Injection/Baghouse Collection Pilot on Stoker-Fired Boiler, 1976 - Present

Scope

Carborundum (now a division of Kennecott Development Company) has tested a dry injection/baghouse collection system using 100 acfm slipstream from a small stoker-fired boiler near their Knoxville, Tennessee offices. A larger, 1000 acfm baghouse has been installed, and dry injection testing is continuing at this scale. The 100 acfm unit was also equipped for spray dryer/baghouse testing, and current plans are to equip the 1000 acfm unit with a spray dryer as well.

Process Description

Dry injection/baghouse collection studies have been completed with sodium bicarbonate, nahcolite, and ammonia sorbents. The smaller (100 acfm) baghouse is an industrial size unit, with small bags. The larger (1000 acfm) baghouse has 4 to 6 full size (11½-inch by 32-foot) bags. A small Bowen spray dryer employing rotary atomization was used for spray dryer testing on the 100 acfm scale.

Information Sources

Blythe, Gary. Telephone conversation with Don Boyd, Carborundum, May 16, 1979.

Blythe, Gary. Telephone conversation with Hank Majdeski, Carborundum, July 6, 1979.

Majdeski, H. M. Personal communication with Gary Blythe, July 17, 1979.

4.2 SPRAY DRYING/PARTICULATE COLLECTION

4.2.1 Atomics International (Rockwell) at Mohave Station, 1972

Scope

Under an agreement with Southern California Edison (SCE), Atomics International conducted pilot plant test work of their (AI's) aqueous carbonate process (ACP). The test work was conducted at SCE's Mohave Generating Station in the first half of 1972. Funding was provided by the WEST (Western Energy Supply and Transmission) Association of utilities.

The major objective of the test program was to determine optimum operating conditions for the spray dryer scrubber using aqueous sodium carbonate solutions for removal of SO_2 from flue gases. The operating results were also to be used in designing a full-scale open-loop ACP process.

Process Description

In the open-loop (no sorbent regeneration) ACP process, the SO_2 is removed by contacting the hot flue gas with an atomized solution of sodium carbonate (Na_2CO_3). The dry product formed is a combination of sodium sulfite, sodium sulfate, and unreacted reagent.

The Mohave test installation included a 23-year old modified spray dryer, 5 feet in diameter, a sodium carbonate feed system, and a multicyclone solids collection system. A slipstream of flue gas, obtained downstream of the station ESPs was fed to the spray dryer. Provisions were made for SO_2 spiking, and for testing at various temperatures. SO_2 concentrations were continuously monitored.

Parameters Investigated

The test work was designed to investigate the following paramters with respect to their effect on SO_2 removal and system performance:

- sorbent concentration,
- stoichiometry,
- inlet flue gas temperature,
- flue gas flow rate,
- concentration of SO_2 in inlet gas, and
- recycle of products to feed.

One series of tests was conducted with the objective of demonstrating effective scrubber performance under optimum design conditions.

Test Conditions

The flue gas flow rate varied from 1150 to 1375 scfm at an inlet temperature ranging from 250 to 340°F. The inlet SO_2 concentration was usually about 400 ppm, except for testing to determine the effects of higher SO_2 concentrations, in which case concentrations of up to 1465 ppm SO_2 were used. Temperature drop across the spray dryer was usually between 120 and 160°F. However, when operation in the "wet" mode (>25 percent moisture in the product) was required to meet particulate removal requirements in the downstream cyclone, the temperature drop was 180°F (although the exit gas was always maintained at least 25°F above its dew point.) Inlet gas moisture content was about 10 percent by volume. A liquid-to-gas ratio of 0.3 gal/1000 scf was employed in most tests. The weight percent of Na_2CO_3 in the feed solution varied between 4 and 5.5, except in the tests investigating the effects of sorbent concentrations where it varied between 20 and 32 percent.

Results

The results of sorbent concentration testing with 400 ppm SO_2 flue gas indicated that equivalent SO_2 removal could be achieved more efficiently with low weight percent solutions. The most efficient SO_2 removal from 400 ppm SO_2 flue gas at 300°F was obtained with a 4 percent weight Na_2CO_3 solution. This solution concentration gave a stoichiometric ratio (Na_2CO_3 to SO_2) of about 1. A lower temperature flue gas would require a more concentrated solution to avoid saturating the exit gas. Higher inlet SO_2 concentrations would also require a more concentrated feed solution for the same degree of removal.

A larger temperature drop over the spray dryer resulted in increased removal efficiency. At a fixed feed rate, lowering the inlet gas temperature also increased removal efficiency. In both cases, the increased wet contact time enhanced removal.

At a constant feed rate of a 5.4 percent weight Na_2CO_3 solution, increasing the gas flow rate from 1150 to 1300 scfm resulted in a linear increase in removal efficiency.

Sorbent utilization was found to increase as the inlet SO_2 concentration increased. In some cases, utilization exceeded 100 percent. The authors suggest that this may be the result of sodium bisulfite ($NaHSO_3$) formation.

Recycled sulfate product salts did not inhibit removal of SO_2. Some results indicated that sorbent utilization increased as the recycle amount increased.

Reasonably consistent results showed two to three percent NO_x removal under most conditions, although the accuracy of the analytical methods available was suspect.

In the series of tests designed to demonstrate system performance under optimum conditions, 90 percent SO_2 removal efficiency was regularly achieved using a 5.3 percent weight Na_2CO_3 solution at an L/G of 0.3 gal/1000 scf and a stoichiometric ratio of 1.15. The total system pressure drop was between 9 and 11 in. H_2O. During these tests it was established that higher atomizer wheel speeds increased removal efficiencies. No mechanical or maintenance problems were encountered during the testing. Additive utilization approached 90 percent.

Conclusions and Comments

The spray dryer was shown to be an efficient method of contacting a dilute Na_2CO_3 solution with hot flue gas for SO_2 removal. For a fixed feed rate, maximum removal efficiency occurred at lower inlet gas temperatures. Both additive utilization and removal efficiency were near 90 percent.

The Mohave facility was equipped with a multi-cyclone collector which sometimes required the spray dryer to operate in the "wet" mode ($>$ 25 percent H_2O in the product) to achieve the required particulate removal requirements.

Information Sources

Gehri, D.C. and J.D. Gylfe. Pilot Test of Atomics International Aqueous Carbonate Process at Mohave Generating Station. Final Report AI-72-51, Atomics International Division/Rockwell International, Canoga Park, CA. September 1972.

4.2.2 Koyo Iron Works, Pilot-Unit, 1973

Scope

Performance characteristics of a spray drying process with NaOH and Na_2CO_3 aerosols was studied by Koyo Iron Works in Japan. The tests were carried out on a pilot-scale facility during 1973.

Process Description

Flue gas from a 3000 lb steam/hr oil-fired boiler was passed through a spray dryer for removal of SO_2 by reaction with NaOH or Na_2CO_3 droplets. A two-fluid atomizer was used to disperse the liquid from the top of the dryer into the flue gas. The gas, containing dry product solids, then passed through a multi-cyclone and an electrostatic precipitator to remove the solids. The dry powder collected was a mixture of Na_2SO_3, Na_2CO_3 and Na_2SO_4.

Parameters Investigated

The parameters investigated in the tests included:

- inlet sulfur dioxide concentration,
- temperature drop across the dryer, and
- stoichiometric ratio (ratio of NaOH fed to theoretical amount needed to react with all incoming SO_2).

Test Conditions

The flue gas flow rate was about 850 scfm in all cases. The temperature of the gas varied from 320 to 428°F. The fuel oil for the boiler contained 1 to 3 percent sulfur, resulting in inlet SO_2 concentrations of from 600 to 1700 ppm.

Results

Sulfur dioxide removal was reported to increase as the stoichiometric ratio or inlet SO_2 concentration increased. An SO_2 removal of 89 percent was reported for flue gas containing 1300 ppm SO_2. The stoichiometric ratio required for this removal was 1.2. At the same inlet SO_2 level, but with a stoichiometric ratio of 1.0, removal decreased to 84 percent. The outlet flue gas was 278°F in both cases, resulting in a 80°F temperature drop over the dryer.

At constant inlet gas temperature, it was found that sulfur dioxide removal increased as the temperature drop across the dryer increased. This reflects the increase in stoichiometric ratio that occurs when feed rate is stepped up to obtain a lower outlet gas temperature (greater ΔT). It was also observed that for a constant temperature drop over the dryer, a lower inlet gas temperature resulted in greater removal efficiency. This is attributed to the lower water evaporation rate at the lower temperature, thus allowing more reaction time in the liquid droplet where the bulk of the sorption reaction occurs. A summary of the magnitude of the temperature effects is presented in Table 4-6.

TABLE 4-6. TEMPERATURE EFFECTS ON SO_2 REMOVAL - KOYO SPRAY DRYER[10]

SO_2 Removal (%)	Inlet Gas Temperature (°F)	Temperature Drop Over Spray Dryer (°F)
86	320	146
74	320	108
81	356	153
69	356	108
79	374	153
68	374	115

The product composition was given as 70 to 80 percent Na_2SO_3, 10 to 20 percent Na_2CO_3 and 5 to 15 percent Na_2SO_4. It was suggested that the collection particles could be used as chemicals in a Kraft or sulfite pulping process.

The authors reported 99 percent collection efficiency for the ESP downstream from the multi-cyclone.

Conclusions and Comments

The sulfur dioxide removals and utilizations reported show spray drying to be an efficient method of sorbent-gas contacting. The report states that either sodium hydroxide or sodium carbonate may be used as the sorbent, but it is not absolutely clear which was used for the data reported.

Information Sources

Isahaya, E.F., "A New FGD Process by a Spray Drying Method Using NaOH Aerosols as the Absorbing Chemical," Staub Reinhaltung der Luft (in English), 33(4), April 1973.

4.2.3 Rockwell/Wheelabrator-Frye at Leland Olds Station, 1977-78

Scope

The primary objective of the Leland Olds pilot plant was to demonstrate the applicability of Rockwell's open-loop Aqueous Carbonate Process (ACP) on an existing lignite-fired boiler. The tests were conducted on Unit 2 at Basin Electric's Leland Olds Station in Stanton, ND during 1977 and 1978. The results of the test work were used in designing a full-scale FGD system for the proposed Coyote Station of the consortium headed by Otter Tail Power Company and to be located in Beulah, ND.

Sodium carbonate and trona were used as the scrubbing media for demonstration tests. Another series of tests was conducted to explore the feasibility of less costly sorbents such as lime or limestone. Also, a week-long endurance test (using trona) was conducted to demonstrate long term reliability.

Process Description

The open-loop ACP includes a spray dryer for contacting the atomized sorbent solution with hot SO_2-laden flue gas and a downstream solids collection device to remove fly ash and entrained product solids. At Leland Olds the collection device was a Wheelabrator-Frye two-compartment fabric filter with a total filter area of 1098 ft^2. The bags were cleaned by reverse air-shaking methods. The spray dryer was a 7-ft diameter Bowen model equipped with a rotary atomizer. The clean flue gas vented to the stack from the filter did not require reheat, nor did the gas exiting the spray dryer as it was usually maintained about 40°F above the dew point.

Tests were conducted on a 2 MW (6000 acfm) sidestream of flue gas from a 440 MW cyclone boiler burning North Dakota lignite.

Scrubber feed was prepared by dissolving or slurrying sorbent in a makeup tank from which it was pumped to the scrubber. In the open-loop process the solids are discarded or sometimes used for recycle.

Parameters Investigated

Test subprograms included sodium carbonate tests, trona tests, hydrated lime and limestone tests, and trona endurance tests. The parameters investigated in each series are listed below.

1) Sodium Carbonate, Trona, and Hydrated Lime and Limestone Tests

   - sorbent concentration
   - inlet SO_2 concentration
   - inlet temperature of flue gas
   - temperature drop over the dryer
   - flue gas flow rate (except for lime/limestone tests)

2) Endurance Tests with Trona

   - inlet SO_2 concentration
   - inlet temperature of flue gas

Test Conditions

Table 4-7 lists test conditions for the various series.

TABLE 4- 7. OPEN-LOOP ACP PILOT-PLANT TEST CONDITIONS - ROCKWELL AT LELAND OLDS[4]

Series	Sorbent Concentration (wt %)	Inlet SO_2 Conc. (ppm)	Flue Gas Flow acfm	Dryer Inlet (°F)	Dryer ΔT[a] °F
Sodium Carbonate	4 to 22	900 to 2300	1500, 2500 & 3100	260 to 350	90 to 170
Trona	7 to 12	800 to 1400	1500 to 2500	250 to 350	100 to 170
Hydrated Lime and Limestone	3, 5 & 10	600 to 2000	2500	310 to 350	120 to 170
Trona Endurance Tests	8 to 18	700 to 1400	2400 to 2500	293 to 329 (with boiler operation)	100 to 130

[a] The difference in flue gas temperature between the spray dryer inlet and outlet.

Results

Although specific findings of this study are considered proprietary information, overall the open-loop ACP was demonstrated to be an effective SO_2 removal method. Trona and sodium carbonate were equally effective in removing SO_2 with up to 85 percent of the SO_2 being removed in the spray dryer and an additional 10 to 20 percent removal occurring on the fabric filter cake. Sorbent utilizations ranged from 80 to 100 percent. In all cases the product was a dry, free-flowing powder.

Hydrated lime was not as effective an absorbent as the sodium alkalis on a once-through basis. Removals were in the 45 to 60 percent range and were accompanied by low additive utilization. The single test in which limestone was used gave poor SO_2 removal despite a high stoichiometric ratio.

The parameters that seemed to influence the reaction of SO_2 with material collected on the filters were filter temperature, pressure drop, gas flow rate, and sorbent utilization in the spray dryer. An increased temperature drop across the spray dryer, caused by increasing liquid rate, increased removal.

The endurance test with trona was successful. No degradation of SO_2 removal or serious equipment malfunction was observed.

Conclusions and Comments

The open-loop ACP was shown to be a viable SO_2 removal process. The additional removal occurring in the filter cake did not affect baghouse performance.

As a result of this and subsequent test work at the Leland Olds pilot-plant facility, Rockwell/Wheelabrator-Frye was awarded a contract to design and build a full-scale open-loop ACP system at the proposed Coyote Station. The system is to be completed in spring, 1981.

Information Sources

Dustin, D.F., Report of Coyote Pilot Plant Test Program, Test Report, Rockwell International, Atomics International Division Canoga Park, CA, Nov. 1977.

4.2.4 Joy/Niro at Hoot Lake Station, 1977-1978

Scope

In late 1977 Joy Manufacturing and its Western Precipitation Division entered into an exclusive agreement with Niro Atomizer to design and market dry FGD systems. Niro had begun test work using a spray dryer for FGD applications in 1974, on the 1000 to 3000 acfm scale, at their Copenhagen facility. The tests investigated various alkaline sorbents such as lime, limestone, and sodium carbonate. During the six-month period of November 1977 to April 1978 Joy/Niro designed, constructed, and operated a pilot plant test facility at Otter Tail Power Company's Hoot Lake Station in Fergus Falls, Minnesota. The purpose of this pilot unit was to demonstrate the viability of the Joy/Niro process and to provide the design basis for a bid on a commercial unit to be constructed at Basin Electric's Antelope Valley Station. Additional test work was conducted during the period of September to December 1978 to acquire data for preparation of a bid for a dry FGD system for the Basin Electric Laramie River Station.

Process Description

Flue gas from a 53 MW CE boiler was supplied to the spray dryer at an average rate of 20,000 acfm. The gas temperature was 310°F. The Joy/Niro dry FGD process consists of a spray dryer absorber equipped with a Niro atomizer and a Joy baghouse that was used for collection of solids from the existing flue gas.

The process flow diagram for the Hoot Lake test facility is shown in Figure 4-2. Hot flue gas entered through a roof gas disperser and contacted the atomized slurry. Some of the dry product was collected at the conical bottom of the spray dryer, the rest being swept out with the exiting flue gas and collected, along with the fly ash present, in the downstream baghouse or electrostatic precipitator (ESP). The quantity of slurry was controlled using variable speed Moyno pumps to maintain the flue gas outlet temperature at 30°F to 40°F above saturation.

The spray dryer used was 11.25 ft in diameter and was equipped with a Niro atomizer coupled to a variable speed motor. The four-compartment baghouse had a 9000 acfm capacity with bag cleaning by both reverse-air and shaking methods. Both acrylic and fiberglass bags were tested with no difference in performance observed. The ESP employed in some tests was a single field unit capable of handling up to 5000 acfm of flue gas.

Parameters Investigated

The testing was conducted in two phases. First, a series of short (10-12 hr) tests covering the expected operating ranges were performed. The second phase consisted of a 100-hr endurance test conducted to determine the ability of the system to meet maximum SO_2 removal requirements

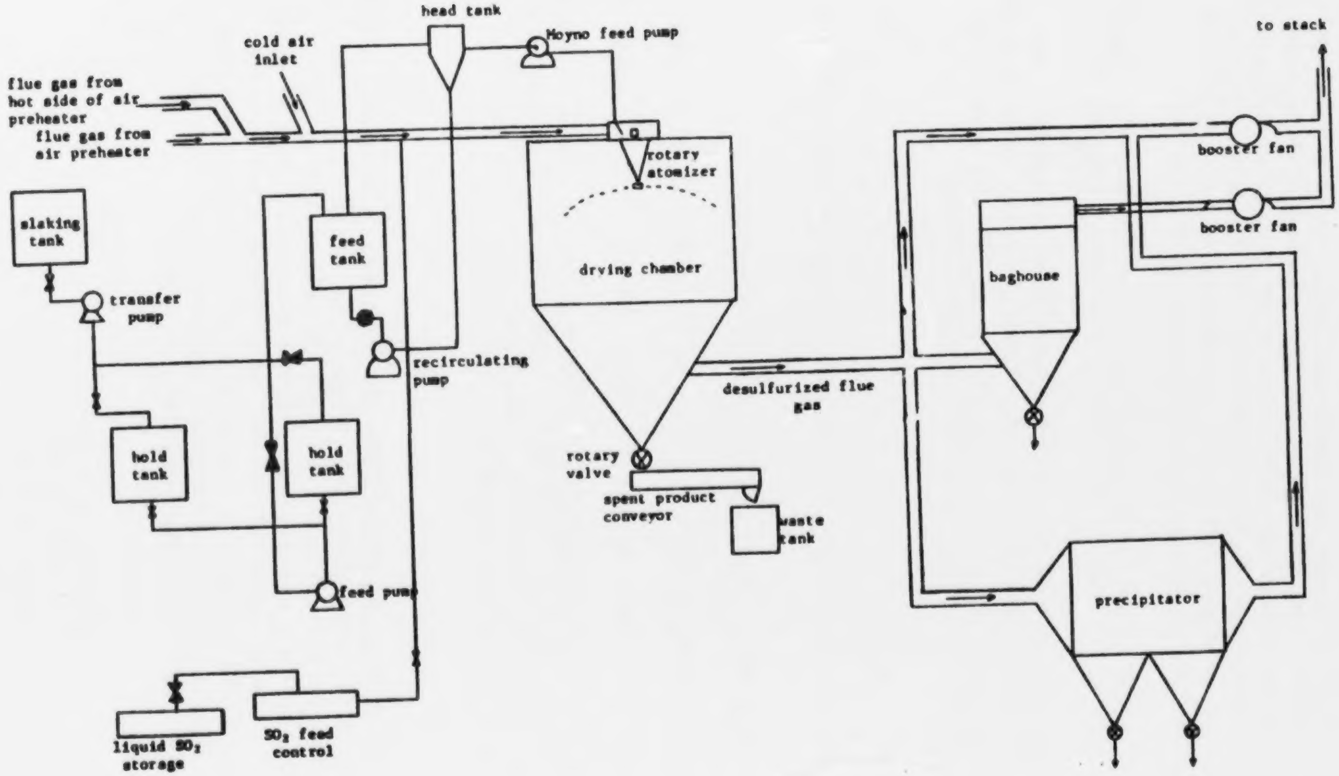

head tank
Moyno feed pump
to stack
cold air inlet
flue gas from hot side of air preheater
flue gas from air preheater
rotary atomizer
booster fan
booster fan
slaking tank
feed tank
drying chamber
baghouse
transfer pump
recirculating pump
desulfurized flue gas
hold tank
hold tank
rotary valve
spent product conveyor
waste tank
feed pump
precipitator
liquid SO_2 storage
SO_2 feed control

Figure 4-2. Hoot Lake pilot plant flow sheet.[3]

during continuous operation.

The first phase of tests was conducted using various types of lime and lime-slaking methods. Optimum hydration/lime-slaking methods were determined for use in the 100-hr endurance test. The other parameters investigated during the first phase were spray dryer inlet temperature, flue gas tamperature drop across the spray dryer, SO_2 inlet concentration, flue gas flow rate, sorbent concentration, atomizer speed and wheel configuration.

Additional short tests were conducted to investigate the Joy/Niro solids recycle concept. Figure 4-3 depicts the recirculation flow scheme.

Tests using soda ash as the sorbent were also conducted. As a final verification of process reliability, two types of upset condition testing were performed to check 1) the control system and 2) the effects of low spray dryer exit gas temperature on baghouse performance.

Test Conditions

The primary variables used in the first phase of test work are listed below:

SO_2 Inlet Concentration: 800, 1200, and 1600 ppm/v

Lime Slurry Concentration: 5, 10, 15, 20, and highest possible wt %

Temperature Difference Across the Spray Dryer: 70, 105, 140, and 175°F

These test conditions were specifically related to the proposed Antelope Valley dry scrubbing system. Additional test work was conducted over a wide range of conditions. SO_2 inlet concentration varied from 200 to 4000 ppm and the stoichiometric ratio was varied from 0.9 to 3.0.

Results

Specific correlations between SO_2 removal and stoichiometric ratio at a given SO_2 level were not available. The results presented in the literature covered wide ranges of SO_2 levels but gave only general removal figures. For a "once-through" system, the SO_2 removal was reported to be 90 percent at an inlet SO_2 concentration from 200 to 2000 ppm with a stoichiometric ratio of 2.0 to 3.0, depending on the gas temperature drop across the dryer. Removal versus stoichiometric ratio curves were presented for "typical" cases, but they were not accompanied by SO_2 concentration levels.

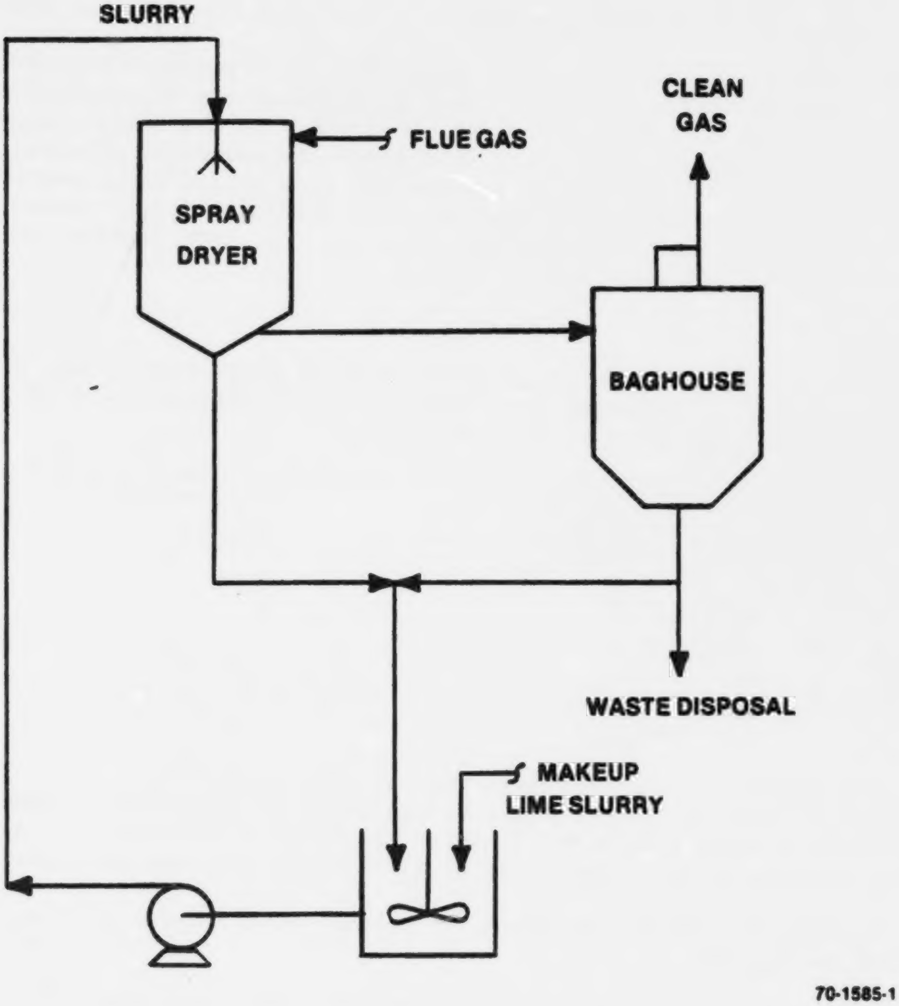

SLURRY
CLEAN GAS
FLUE GAS
SPRAY DRYER
BAGHOUSE
WASTE DISPOSAL
MAKEUP LIME SLURRY
70-1585-1

Figure 4-3. Flowsheet of pilot-plant operation with partial solids recycle.[3]

Because of the limited data available, only general trends can be presented:

1) Additive utilization was significantly improved in tests where partial recycle of solids was employed. Ninety percent removal was obtained with stoichiometric ratios between 1.3 and 1.7.

2) Soda ash was found to be much more reactive than lime, with stoichiometric ratios of 1.0 to 1.2 resulting in 90 percent SO_2 removal at inlet SO_2 concentrations ranging from 800 to 3000 ppm.

3) Increasing the temperature drop over the dryer at a constant stoichiometric ratio was fo-nd to increase the SO_2 removal. For an example of this trend see Table 4-8. If the outlet temperature of the gas is taken to be 30°F above the adiabatic saturation temperature of 130°F, a temperature drop of 155°F corresponds to a dryer inlet flue gas temperature of 315°F, very near normal operating flue gas temperature at both the Hoot Lake Station and the proposed Antelope Valley Station.

TABLE 4-8 THE RELATIONSHIP BETWEEN SPRAY DRYER TEMPERATURE DROP AND SO_2 REMOVAL AT A CONSTANT STOICHIOMETRIC RATIO OF 2.5 JOY/NIRO AT HOOT LAKE[3]

Spray Dryer ΔT (°F) Temperature Difference	SO_2 Removal (%)
155	90
125	75
105	60

The control system responded well to upset conditions, such as a large temperature drop in the inlet gas to the dryer or operation at temperatures low enough to result in a wet product. Baghouse performance was not affected during periods of "wet" operation as the exiting gas remained unsaturated.

Particulate removal exceeded 99+ percent in all cases with both baghouse and ESP collection.

During the mid-September to mid-December 1978 test period, coal from the source to be used at the proposed Laramie River Station was shipped to the Hoot Lake Station for use in several days of test runs. The Laramie River ash was reported to be quite cementitious, but no operating problems were reported. Some tests were conducted adding water treatment sludge to the atomizer feed. This was found to be a suitable method of handling for the sludge.

In limited test work with commercially available ground limestone the best SO_2 removal obtained was 50 to 60 percent.

Conclusions and Comments

The Joy/Niro dry FGD system performed well during pilot plant parametric and endurance testing. No major problems were encountered with the equipment or process chemistry.

Though no specific removal data were given, it appears that 85 percent SO_2 removal was achieved with near theoretical amounts of lime when partial recycle of solids was employed. The exact removal is, of course, dependent on the inlet SO_2 concentration among other factors.

The literature also states that the "initial" stoichiometric ratios were considered conservative due to large air leakages. It is not clear at what point during the test period this problem was corrected.

It was also concluded that the method of lime slaking is an important factor in determining the effectiveness of lime as a sorbent.

Sulfur dioxide removal is limited by, among other factors, the amount of slurry that can be supplied to the dryer. To avoid moisture condensation in downstream particulate removal equipment or stack, the slurry delivery rate must be maintained below levels that would cool the flue gas below its adiabatic saturation temperature.

After the Hoot Lake Station test work was completed, Joy/Niro bid on and was awarded a contract for a 440 MW commercial dry FGD system to be built at Basin Electric's proposed Antelope Valley Station. The system to be constructed will be a large-scale version of the pilot plant facility described above with the only major change being the method of gas dispersion into the spray dryer. See Section 5.12 for further details on this commercial system.

Information Sources

Blythe, Gary. Meeting notes, meeting at Joy Manufacturing, June 14, 1979.

Davis, R.A., et al., "Dry SO_2 Scrubbing at Antelope Valley Station," presented at the American Power Conference, April 25, 1979.

Felsvang, Karsten, "Results of Pilot Plant Operations for SO_2 Absorption," presented at the Joy Western Precipitation Division Seminar, Durango, CO, May 21, 1979.

Kaplan, Steven, "The Niro-Joy Spray Absorber Development Program - Pilot Plant Description and Test Results," presented during Joy/Niro-sponsored tour for executives of U.S. power industry, Copenhagen, Sept. 23-30, 1978.

4.2.5 Babcock and Wilcox, Pilot Scale Spray Dryer/ESP at Velva, 1978

Scope

B&W was one of four vendors which piloted a spray dryer-based dry FGD system at Basin Electric. B&W began testing at the Basin Electric's William J. Neal Station, near Velva, N.D., using technology developed by Hitachi of Japan. This pilot plant eventually employed two-fluid nozzles for atomization and a horizontal reactor chamber, whereas the Hitachi process employed nozzle atomization in a vertical reactor. Gas flow out of the Hitachi reactor was through a duct in the bottom of the vessel, which tended to plug during testing. This led B&W to abandon the Hitachi configuration and instead adapt the steam atomized oil burner ("Y-jet" nozzle) technology in a horizontal reactor. Figure 4-4 illustrates the Y-jet nozzle configuration.

Process Description

The reactor at Velva was 30.5 ft long by 5.75 ft square, with one atomizing nozzle and three hoppers located in the floor to handle solids drop out. The gas capacity of the unit was 8000 acfm. While the Hitachi reactor was tested with both a 16-bag Mikropul pulse jet baghouse and an ESP collector, the Y-jet configuration was tested only with an ESP collector. Reagents tested included soda ash, pebble lime, hydrated lime, ammonia addition with lime, and precipitated limestone. A ball mill slaker was used for lime slaking. Reactor inlet and outlet gas temperatures, inlet SO_2 concentration, gas flow, and sorbent stoichiometry were also varied during the test program.

The Y-jet configuration pilot unit began operation in June 1978. Future studies include full parametric studies on a 1500 acfm pilot plant at the company's research facilities in Ohio and a 120,000 acfm demonstration unit treating flue gas from a 500 MW unit at a large western utility. Details of these programs are discussed in Section 5.

Results

Because the results of this privately funded research effort are considered proprietary, no specific performance results are available. However, it was found that due to reagent costs, lime was the preferred reagent. Also, B&W found that they could operate more comfortably near adiabatic saturation at the reactor outlet when using an ESP rather than a bag collector for downstream particulate collection. The increase in reagent utilization due to closer approach to saturation was found to be greater than that resulting from SO_2 removal on a bag collector surface. Apparent utilizations approaching or even exceeding 100% were found to be possible during lime tests when the reactor outlet temperature closely approached saturation. Utilizations greater than 100% may be due to the alkaline species in the recycled fly ash reacting with the flue gas SO_2.

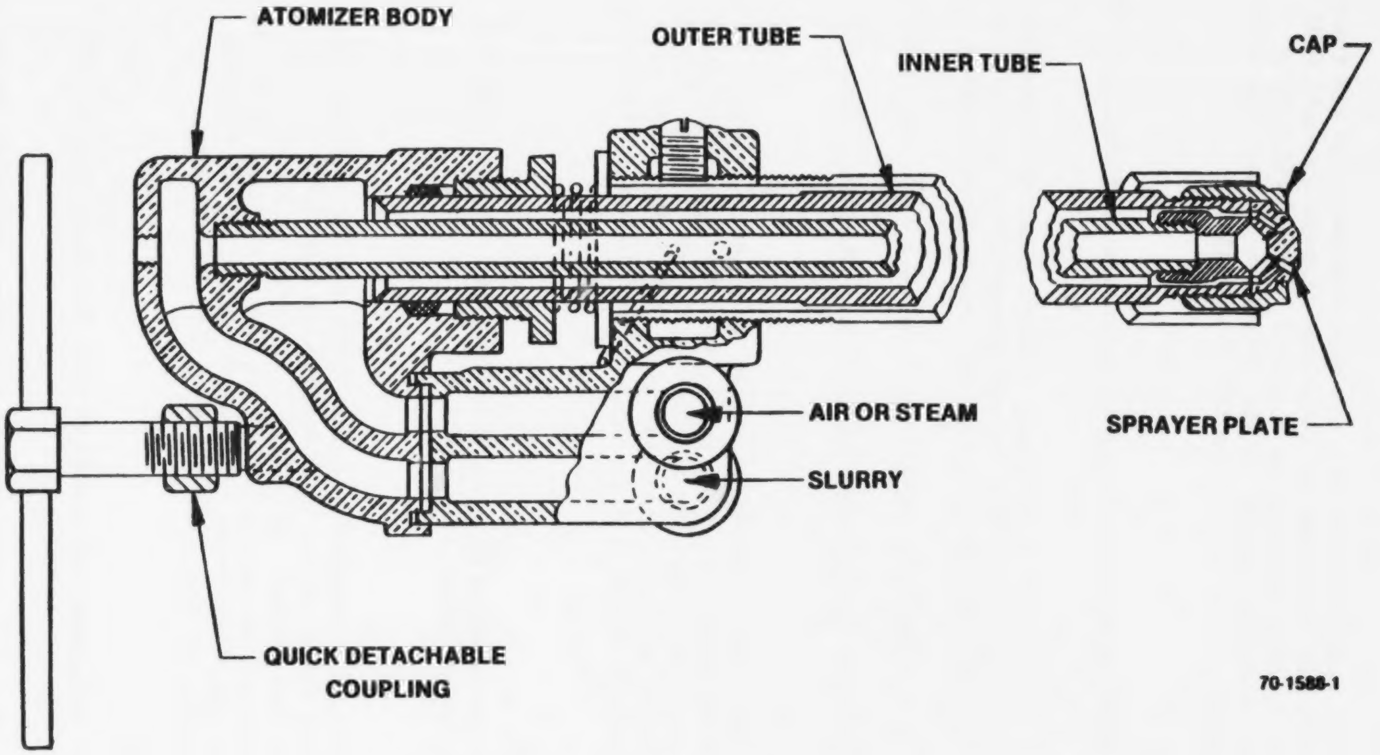

ATOMIZER BODY
OUTER TUBE
INNER TUBE
CAP
AIR OR STEAM
SPRAYER PLATE
SLURRY
QUICK DETACHABLE COUPLING
70-1588-1

Figure 4-4. "Y-jet slurry atomizer."[11]

In test work using only recycled fly ash as a reactant, it was found that fly ash reactivity was increased by recycling through the ball mill slaker rather than by recycle directly as a slurry. Presumably, this increase was at least partially caused by the reduction in particle size resulting from treatment of the fly ash in the ball mill.

Information Sources

Blythe, Gary. Meeting notes, meeting at Babcock and Wilcox, June 28, 1979.

Janssen, Kent E. and Robert L. Eriksen, "Basin Electric's Involvement With Dry Flue Gas Desulfurization," paper presented at the Fifth EPA Symposium for Flue Gas Desulfurization, Las Vegas, Nevada, March 5-8, 1979.

Slack, A.V., "A.V. Slack FGD Report #62," January 1979, pp. 15-30.

4.2.6 Carborundum/DeLaval Spray Dryer Pilot Plant at Leland Olds, 1978

Scope

As one of the four process vendors invited to pilot a spray dryer-based FGD system for bidding on the Coyote station, Carborundum participated in pilot testing with a 15,000 acfm unit at the Basin Electric's Leland Olds Station. The pilot unit employed a DeLaval spray dryer as a flue gas contactor. A Carborundum baghouse was used as a particulate collection device.

Process Description.

The pilot unit was a spray dryer baghouse system. Lime, soda ash, and ammonia were tested as sorbents.

Results

The lime tests by Carborundum at Leland Olds are significant because a wide range of spray dryer outlet temperatures were tested. Outlet temperatures ranged from around 122°F (a 4°F approach to saturation) to over 200°F (90°F approach to saturation). SO_2 removal varied from 55 percent to 91 percent (stoichiometric ratio of about 1, inlet SO_2 of 700 ppm). Higher removals occurred at the lower dryer outlet temperatures.

Information Sources

Blythe, Gary. Telephone conversation with Don Boyd, Carborundum, May 16, 1979.

Blythe, Gary. Telephone conversation with Hank Majdeski, Carborundum, July 6, 1979.

Majdeski, H.M. Personal communication with Gary Blythe, July 17, 1979.

4.2.7 Bechtel Power Company, Conceptual Spray Dryer/Baghouse and Dry Injection/Baghouse Study, August 1978 to Present

Scope

Bechtel is being funded by EPRI in a economic study comparing various spray dryer-based and dry injection-based dry FGD systems with a wet limestone scrubber. Initial work was begun in August 1978; a final report is expected by the end of 1979. Most of the economic cases were for a hypothetical 500 MW, 85 percent SO_2 removal unit, although two 200 MW cases were calculated. Four coals were considered, ranging from 0.5 to 4.0 percent sulfur. Trona and nahcolite sorbents are being considered for the dry injection cases, lime and soda ash sorbents are being considered for the spray dryer cases.

The study compares capital and operating costs of the dry systems to a wet limestone scrubber. Also, the study considers the engineering aspects of applying dry FGD, such as integration of the unit with the utility boiler.

Information Sources

Blythe, Gary. Telephone conversation with Navin Shah, EPRI, July 20, 1979.

4.3 OTHER RESEARCH

This area includes test work with bench- or pilot-scale bed reactors and combustion of a coal/limestone fuel.

4.3.1 FMC Corporation, Bench-Scale Fixed Bed, June 1970

Scope

During the period of June 1969 to July 1970, FMC Corporation undertook a series of bench-scale screening tests designed to evaluate potential SO_2 sorbents. The study was funded by the National Air Pollution Control Association (now EPA).

Process Description

The experimental apparatus was designed to evaluate the sorption characteristics of a given material in less than an hour. The sample holder was a vertically mounted stainless steel tube 4 inches long and 1/2 inch in diameter. The sorbent was supported on a sintered steel plate near the bottom of the tube. Synthetic flue gas, prepared by blending bottled gases, was passed through the fixed bed of sorbent.

Parameters Investigated

Various types of sorbents were tested: sodium carbonates, impregnated silica gels, impregnated fly ash, hydroxides, and sulfides.

Test Conditions

All experiments were carried out with one gram samples of sorbent. The gas flow rate was about 0.6 ft^3/sec with an inlet SO_2 concentration of 3500 ppm at 257°F. The "typical" dry gas composition was 82.7 percent N_2, 14.9% CO_2 and 3.0% O_2. The moisture content was 4 or 6 mole percent.

Results

Table 4-9 lists the sodium-based materials tested, the SO_2 outlet concentration after 25 minutes, the duration of the test run, and the sorbent utilization at test completion. The sodium carbonates were considerably more effective than any of the other materials tested.

Conclusions and Comments

The results of this study indicate significant sorption of SO_2 by "fixed-bed" samples of sodium carbonate and sodium sesquicarbonate. Natural soda ash and sesquicarbonates were superior to the commercial carbonates, both in amount of SO_2 absorbed after a given time and in utilization of the sorbent.

Information Sources

Friedman, L.D., Applicability of Inorganic Solids Other Than Oxides to the Development of New Processes for Removing SO_2 from Flue Gas, FMC Corporation for the National Air Pollution Control Administration, Contract No. CAA 22-69-02, Princeton, NJ. December 1970.

4.3.2 Nagoya Institute of Technology, Multi-Stage Bed, September 1973

Scope

In 1973, bench-scale studies were conducted to evaluate the use of soda ash in removing SO_2 from air in a multi-stage bed. Also, the rate of SO_2 sorption was investigated in bench-scale equipment.

Process Description

The active soda ash was added to the top stage of the bed and moved to lower levels with rakes. The dimensions of the apparatus were not available. The test gas was air with controlled amounts of SO_2 and water vapor added to achieve the desired composition.

TABLE 4-9. RESULTS OF SCREENING TESTS ON SODIUM CARBONATE AND SODIUM SESQUICARBONATE - FMC CORPORATION[6]

Reactant	SO_2 Inlet Conc. (ppm)	SO_2 Outlet Conc. After 25 Min. (ppm)	Duration of Test (minutes)	Stoichiometric Utilization[a] (percent)
FMC Soda Ash Grade 50[b]	3500	2694	72	30
FMC Soda Ash Grade 120	3500	2497	45	33
FMC Soda Ash Grade 100	3500	2688	744	42
Precipitation Cake[c]	3500	2120	91	78
Natural Ash[d]	3500	1765	70	64
FMC Sodium Sesquicarbonate	3500	1879	746	81
FMC Anhydrous Sesquicarbonate	3500	1688	97	91

[a] Based on moles of Na_2O fed per mole SO_2 fed in the gas.

[b] Less porous than Grade 100 or 120.

[c] Impure sodium sesquicarbonate (impure $Na_2CO_3 \cdot NaHCO_3 \cdot 2H_2O$).

[d] Calcined trona.

Parameters Investigated

The tests were conducted to investigate the effects of the following on SO_2 removal:

- concentration of water vapor,
- particle size,
- temperature, and
- mole ratio of soda ash to inlet SO_2.

Test Conditions

Table 4-10 provides the experimental schedule. Inlet SO_2 concentration varied from 1050 to 2460 ppm.

Results

Table 4-11 lists the results of the test work. Removals of 97+ percent were reported for all conditions.

In other tests with a thermobalance, active soda ash was found to absorb SO_2 at the rate of 1 mg/cm^2-min below 170°C (338°F). Soda ash containing up to 50 percent sodium sulfite absorbed SO_2 as fast as pure soda ash. When more than 50 percent sulfite was present, the absorption rate fell off slowly. Sulfite was oxidized to sulfate at temperatures above 428°F.

Conclusions and Comments

The study concluded that the multi-stage bed removal method was suitable for small plants. Using the scale-up factors proposed by the researchers, a 330 MW plant with 2000 ppm SO_2 flue gas would require about 14 desulfurizers, each 30 feet in diameter.

Information Sources

Yamada, Tamotsu, et al. Desulfurization of Combustion Exhaust by Active Soda Asn, Nagoya Institute of Technology, Japan, 25 395-403, 1973.

TABLE 4-10. EXPERIMENTAL SCHEDULE - NAGOYA MULTI-STAGE BED[23]

Parameter	Test Number			
	1	2	3	4
A: Water Vapor (%)	6	12	18	24
B: Particle Size (mesh)	-50/+100	-100/+200	-200/+325	-325
C: Temperature (^oF)	308	592	482	572
D: Mole Ratio	1.0	1.2	2.0	2.5

TABLE 4-11. EXPERIMENTAL RESULTS - NAGOYA MULTI-STAGE BED[23]

Parameters				Inlet SO_2 Conc. (ppm)	Outlet SO_2 Conc. (ppm)	(%)
A	B	C	D			
1	1	1	1	1050	18	98.3
1	2	2	3	1550	11	99.3
1	3	3	4	1440	21	98.5
1	4	4	2	1440	17	98.8
2	2	1	4	1650	20	98.8
2	1	2	2	1800	20	98.9
2	3	3	1	2140	14	99.3
2	4	4	3	1540	28	98.2
3	3	1	2	1320	18	98.6
3	4	2	4	1740	11	99.4
3	1	3	3	1590	35	97.8
3	2	4	1	2460	23	99.1
4	4	1	3	1580	10	99.4
4	1	2	1	1760	44	97.5
4	2	3	2	1770	38	97.9
4	3	4	4	2310	20	99.1

4.3.3 Stearns-Roger/Superior Oil, Fixed-Bed and Countercurrent Reactors, 1974

Scope

In December 1973, Superior Oil contracted with Stearns-Roger for the design, construction, and management of a pilot facility of investigate the feasibility of using nahcolite as a stack gas SO_2 removal agent. Bench-scale tests using a fixed bed reactor were conducted to investigate reaction kinetics. A pilot-scale countercurrent reactor was used to verify bench-scale results and to provide data for a conceptual design and a hypothetical 500 MW power plant.

Bench-Scale Test Work

Process description--After passing through a filter to remove particulates, the hot flue gas flowed downward through a thin bed (1-inch deep) of screened and sized nahcolite or sodium bicarbonate. The flue gas flow was large enough with respect to the thin bed so that SO_2 concentration was essentially constant across the bed. Provisions were made for spiking the gas with SO_2 and for heating it to the desired temperature. Portions of the nahcolite bed were withdrawn periodically to yield conversion versus time results.

Parameters investigated--The main parameters investigated were granule size and reaction time. The grade of sorbent (commercial sodium bicarbonate and nahcolite) and SO_2 concentration were also varied. The prime objective was to correlate experimental data with mathematical models to determine the rate controlling step of the reaction.

Test conditions--The nahcolite and sodium bicarbonate granules ranged in size from 10 mesh to 1/2 inch. The SO_2 concentration was varied between 450 and 10,000 ppm.

Results--Comparison of conversion versus time experimental data and predicted results of mathematical models of reaction kinetics led to the observation that the nahcolite-SO_2 reaction is controlled by the diffusion of SO_2 through the layer of sodium sulfate that builds up on the outer surface of the particle. The experimental data correlated very well with the ash diffusion model, whereas the gas-film diffusion and chemical reaction controlled models were not confirmed by data.

Other results suggested that pretreatment of the nahcolite (i.e., by heating to decompose it to the more porous Na_2CO_3) may improve its SO_2 removal capabilities.

Conclusions and Comments--The bench-scale study determined that the $NaHCO_3/SO_2$ reaction is controlled by the diffusion of SO_2 through the sodium sulfate layer that builds up on the particle. This observation only applies to the fairly large particle sizes used; the reaction may be controlled by gas-film diffusion for smaller particles.

Pilot-Scale Test Work

Process description--The pilot-scale countercurrent reactor was 42 inches in diameter. Hot flue gas flowed up through a slowly descending bed of nahcolite or sodium bicarbonate. Since the reactor was insulated, temperature drop was negligible. The solids residence time ranged from 100 to 200 hours. Nahcolite was added to maintain a constant stoichiometric ratio, and spent solids were removed to maintain a constant bed level. Temperature, pressure drop across the reactor, and inlet/outlet SO_2 concentrations were continously monitored.

Paramters investigated--The test variables were:

- temperature,
- inlet SO_2 concentration,
- bed height, and
- flue gas flow rate.

Test conditions-Test conditions are given in Table 4-12.

Results--The results of the four tests conducted are given in Table 4-12. Sulfur dioxide removals of 80 to 84 percent were achieved with less than stoichiometric amounts of sodium bicarbonate. Additive utilization was about 97 percent. The SO_2 removal efficiency was lower in the nahcolite test; 67 percent with 75 percent additive utilization. The investigators pointed out that the purpose of the nahcolite test was to verify the predictive ability of their mathematical model, not to optimize SO_2 removal or additive utilization.

Pressure drops over the reactor ranged from 16 to 22 in. of H_2O. No results were presented as to the effect of varying temperature, bed height, or flue gas flow, although the temperature was 20°F lower in the nahcolite run. Nitrogen oxides removal was reported to be 42 percent in the test with nahcolite, the only run for which such a determination was made.

Conclusions and comments--Although high SO_2 removals with good additive utilization were achieved in the countercurrent reactor, there remain certain disadvantages to the process. The countercurrent reactor is a somewhat mechanically complicated piece of equipment and might be prone to operating and maintenance problems on a full-scale size. Also, the pressure drop over the reactor is much greater than that for dry injection or spray dryer systems.

TABLE 4-12. TEST RESULTS WITH PILOT-SCALE COUNTERCURRENT REACTOR[20]

	Test 1 Sodium Bicarbonate	Test 2 Sodium Bicarbonate	Test 3 Sodium Bicarbonate	Test 4 Nahcolite
Average particle size (cm)	0.43	0.43	0.43	0.37
Bed depth (in.)	36	36	36	42
Flue gas flow (acfm/ft^2)	100	100	100	98
Temperature (°F)	300	300	300	280
Inlet SO_2 (ppm)	810	810	2480	675 (150 ppm NO_x)
Stoichiometric ratio	0.86	0.86	0.82	0.89
SO_2 removal (%)	84	84	80	67
NO_x removal (%)	-	-	-	42
Fly ash removal (%)	-	$\sim$93	-	98.6
Pressure drop (in. H_2O)	18	21	16	22
Additive utilization (%)	98%	98%	97%	75%

Information Sources

Stearns-Roger, Nahcolite Granule Scrubbing System Feasibility Study, Vol. 1, for Superior Oil Company, Nov. 1974.

4.3.4 R. W.E. Tests in Germany

Scope

R. W.E., a German utility company has evaluated various calcium-based alkali materials for removing SO_2 from flue gas by injecting them through low NO_x burners in an existing 60 MWe lignite-fired boiler. R. W.E. has been using limestone for about a year in this process to achieve compliance with local air pollution regulations.

Process Description

This is a very simple process that takes limestone from storage, pulverizes it along with coal, and injects the coal/limestone mixture into the boiler through low NO_x burners. This is a retrofit installation that uses the boiler's existing burners. Process control is simple and straightforward; an instrument is used to monitor outlet SO_2 concentration which in turn regulates the flow of limestone to the coal pulverizer. The coal fired by the utility is a German brown coal which is similar to a low-grade U.S. lignite. Its heating value is reported to vary from 4300-5000 BTU/lb with a sulfur content of 0.4 to 0.7 percent.

Results

R.W.E. has apparently examined the use of three sorbent materials: limestone, lime, and calcium sludge from water treating. Their experience has shown that limestone is the best sorbent for their use due to its superior handling characteristics over the other sorbents.

Results of their testing indicate that SO_2 removals of 60-90 percent can be achieved with stoichiometric calcium to sulfur ratio of up to 3. No time intervals were, however, given for these high removal rates so it may not be known how effective this process will be in achieving high SO_2 removals over long periods of time.

Over the last year, the system has operated well achieving compliance with local air pollution regulations. However, due to the low sulfur coal being burned, coupled with non-stringent SO_2 control requirements, the system has only had to achieve 25-50% SO_2 removal during this time. The stoichiometric ratio required to achieve this level was reported to be about 1. Capital investment costs (including modifications to the particulate control equipment) were reported to be about $150,000 for the 60 MWe system.

Conclusions and Recommendations

Results of the test work described are promising and illustrate the ability of this technique to remove SO_2 without plugging of boiler tube spaces. The major unanswered question is the ability of this technique to achieve the stringent removal levels required by U.S. air pollution regulations under sustained periods of operation. Although it appears that the application of this technique in the U.S. may be limited to only low sulfur Western coals, this technique, if proven, appears to provide a very economical SO_2 removal alternative.

Also, it should be noted that boiler tube spacings for German lignite-fueled boilers are larger than those used in conventional coal-fired boilers. In addition, the flow arrangement is such that the hotest portion of the boiler is not at the "top" of the boiler. Consequently, coal-fired boilers may need to be re-designed to avoid plugging if coal-limestone mixes are to be used successfully.

Information Sources

Dickerman, J.C., Telephone Conversation with R.M. Statnick, U.S. EPA, October 4, 1979.

SECTION 5

CURRENT AND ON-GOING ACTIVITIES

This section summarizes pertinent activities of companies involved in current and on-going developments for dry FGD systems. Included here are background information on the companies, a summary of dry FGD related research, a summary of commercial sales and marketing activities and a description of the type(s) of dry FGD the company is marketing or developing. The current development activities of each of the companies discussed in this section are summarized in Table 5-1.

The discussions of current and on-going development activities are presented in alphabetical order by company name. For companies which have been in the dry FGD business for several years, the information here includes description of substantial research efforts and details of commercial sales. For companies which have only recently entered this market, only a brief discussion of their intentions may be given here. The results of most current activities reported in this section are very preliminary and are unpublished. Consequently, most data were obtained through personal contact, either by telephone or meetings held with process vendors. For this reason, company representatives who may be contacted for additional information on their dry FGD activities are provided.

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Background

B&W was one of four companies which piloted spray dryer-based dry FGD systems at Basin Electric in late 1977. B&W originally tested Japan's Hitachi two-fluid nozzle atomization technology in a Hitachi vertical spray dryer/reactor. When this concept proved inadequate for utility FGD application, B&W developed a horizontal reactor using "Y-jet" steam-atomized nozzles which were adapted from their standard oil burner technology. In this aspect B&W has a rather novel approach to spray drying technology. Other spray dryer-based dry FGD system vendors tend to use more standard spray drying technology with a back-mix type reactor and two-fluid or rotary atomization. B&W also takes a different approach in that they favor ESP collection of the spent sorbent/fly ash mixture rather than baghouse collection which appears to be favored by other vendors.

TABLE 5-1. SUMMARY OF CURRENT R & D AND COMMERCIAL ACTIVITIES

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COMPANY/AGENCY	SYSTEMS(s)/SCALE	LOCATION(s)/DATE(s)	FUNDING	SORBENT	COMMENTS
Babcock and Wilcox	Demonstration: 120,000 acfm spray dryer/ESP.	Western utility: Scheduled for start-up in late 1979.	Internal	Lime, soda ash, sodium-based waste liquor.	Slipstreams from the spray dryer can be routed to either an ESP or a baghouse.
	Research: 1500 acfm pilot unit. Spray dryer/cyclone system mainly for parametric testing and reaction mechanism investigation.	B & W's Alliance Ohio Labs: Initial test work has begun.	Internal	Lime with recycle of solids.	This unit will provide data to better understand the spray drying SO_2 reaction mechanisms.
	Commercial: Constructing spray dryer/ESP full-scale system (500 MW).	Basin Electric's Laramie River Station, Wheatland, Wyoming: Start-up scheduled for spring of 1982.	Basin Electric	Lime.	Designed for 90% SO_2 removal, with a maximum stoichiometry of 1.12. Designed for no recycle.
Buell/Anhydro Joint Venture	Development: Buell/Anhydro is participating in privately funded programs to develop spray dryer based dry FGD system. Initial work completed. Future plans for testing 20,000 acfm dryer.	Initial work done at Anhydro's Copenhagen facilities. Future work planned at Colorado Springs' Martin Drake Station.	Internal	Nahcolite, raw trona (19% $NaHCO_3$) and upgraded trona (92% $NaHCO_3$).	Pending results of test work Buell expects to bid both spray dryer and dry injection systems. Buell has bid a lime spray dryer/baghouse industrial system, but results have not been announced yet.
	Demonstration: 3000 acfm dry injection/baghouse system including sorbent pretreatment and waste treatment studies.	Colorado Springs' Martin Drake Station: Initial test work has been started.	EPA	Nahcolite, raw trona, upgraded trona and lime.	Originally undertaken to study fabric filter removal of particulates. Expanded to study dry scrubbing and related waste disposal.
Combustion Engineering (CE Power Systems)	Development: Installing a 20,000 acfm "dry absorber" followed by baghouse and ESP in parallel.	Northern States Power Sherbourne County Unit #1/Start-up date: July 1979.	Internal	Lime.	C-E also planning dry waste disposal study in conjunction with pilot unit testing.
DOE/Grand Forks Energy Technology Center (GFETC)	Research: 200 acfm dry injection/baghouse system.	GFETC Laboratories: Tests continuing through most of 1979.	DOE	Nahcolite and trona.	GFETC plans to sample for SO_2 and particulate removal efficiencies when Coyote plant starts up (Spring 1981). Also planning waste disposal studies.
DOE/Morgantown Energy Technology Center (METC)	Research: Laboratory studies on passing humidified flue gas through fixed bed of crushed limestone.	METC Labs/Preliminary test work completed.	DOE	Limestone.	No further work is currently planned.
DOE/Pittsburgh Energy Technology Center (PETC)	Research: 500 lb/hr coal-fired furnace being used to test dry injection of various sorbents.	PETC Laboratories/Tests will continue through 1980.	DOE	Sodium carbonate, sodium bicarbonate, raw nahcolite, trona.	Testing is to continue to evaluate dry injection for high sulfur coals. Plans are to add a spray dryer in mid-1980.
Ecolaire Systems, Inc.	Development: 10000 acfm mobile spray dryer/baghouse pilot plant being constructed.	Operation in late 1979 at an as yet unnamed utility.	Internal	Not Specified.	Pilot unit designed for flexibility to establish design data base for dry FGD system for both utility and industrial systems.
Energy and Pollution Controls, Inc.	Development: Totally dry reactor ("slinger" distributes dry sorbent) combined with baghouse. Initial development on flue gas from coal fired 1.6 10^6 Btu/hr boiler. System is for industrial applications.	Development work started in 1978. EPC is continuing test work.	Internal	Hydrated Lime.	Strictly an industrial system.

(continued)

TABLE 5-1. (continued)

COMPANY/AGENCY	SYSTEMS(s)/SCALE	LOCATION(s)/DATE(s)	FUNDING	SORBENT	COMMENTS
Battelle-Columbus Labs	Research: Combustion of coal/limestone pellet in pilot-scale spreader-stoker boilers and 25,000 lb steam/hr industrial spreader-stoker.	EPA and Battelle-Columbus Labs (for 25,000 lb steam/hr boiler)/on-going tests - preliminary work on 20 bhp scale has been conducted to date.	EPA	Limestone	Tests were with Ca:S ratio of 7:1 in the pellet. Further test work will investigate a 3:1 Ca:S pellet. The coal is a high sulfur Illinois coal (6.4% S).
Energy and Environmental Research Corp.	Research: Combustion of a pulverized coal/limestone mixture in a low NO_x burner system. Previous tests conducted on the [illegible] Btu/hr heat input scale. Work continuing on [illegible],000 Btu/hr scale.	EERC labs; on-going work.	EPA	Limestone	Test work will also be conducted on 10 MM and 50 MM Btu/hr scale.
Kerr Industries	Demonstration of 40,000 acfm dry injection/baghouse system.	Unnamed textile finishing plant.	EPA	Lime, Limestone	Baghouse fire has delayed test start. Testing planned for March, 1980.
Joy/Niro Joint Venture	Commercial: The Antelope Valley FGD system (440 MW) is under construction. The process is a spray dryer/baghouse system.	Antelope Valley Station (Basin Electric) Unit 1/Beulah, ND. Start up expected in the spring of 1982.	N/A	Lime (with partial recycle)	Joy/Niro has 2 bids under evaluation, 1 in-house and expects 5 to 6 bid requests by the end of 1979.
	Development: Joy/Niro negotiating to provide a 100 MW scale demonstration unit. Spray dryer followed by baghouse or ESP	Northern States Power's Riverside Station. Scheduled start-up in late 1980.	Not Specified	Lime	
Kennecott, Environmental Products Division (formerly Carborundum)	Development: Stoker-fired boiler producing 1000 acfm of flue gas. Test work being conducted on dry injection/baghouse. Plans call for installing 1000 acfm pilot spray dryer.	Inhouse. Dry injection studies have begun. Spray dryer to be installed in near future.	Internal	Lime	Pending results of pilot test work, EPD may offer commercially both dry injection and spray dryer systems.
Koch Engineering	Development: Work begun on spray dryer based FGD system	Inhouse.	Internal	Sodium hydroxide, Sodium Bicarbonate, Lime.	Koch is reportedly one year away from marketable dry FGD system. Full-scale parametric testing has not yet begun.
Mikropul Corp.	Parametric studies: 1000 acfm spray dryer/pulse-jet baghouse system.	Summit, NJ labs/on-going.	Internal	Lime	Mikropul has no immediate plans to enter utility FGD market.
	Commercial: 40,000 acfm industrial system (spray dryer/pulse-jet baghouse being completed.)	Strathmore Paper Co., Woronoco, MA/Start up in July.	N/A	Lime	
Research-Cottrell Research & Development	Development: 10,000 acfm pilot-scale spray dryer/baghouse system.	Big Brown unit (Texas Utilities)/Pilot unit tests completed.	Internal	Tested various sorbents (Not Specified)	Research-Cottrell is now in a position to begin marketing utility and industrial dry FGD systems.
Rockwell International/Wheelabrator-Frye Joint Venture	Parametric: 4000-5000 acfm spray dryer/baghouse ESP system.	Commonwealth Edison's Joliet Station. Tests begun mid-1979.	Not Specified	Lime, Soda Ash	Mobile unit is primarily for acquiring bid data. RI is also conducting waste disposal studies. RI/WF has 2 bids under evaluation, 1 in-house and expects 5 or 6 requests for bids by the end of this year.
	Design: 5000 acfm mobile pilot spray dryer system.	Operated at Northern States Power's Sherbourne Station and PP&L's Jim Bridger Station.	Not Specified		
	Commercial: The Coyote Station FGD system (410 MW) is under construction. The process is Rockwell's Open Loop ACP (spray dryer/baghouse).	Otter Tail Power Co. Coyote Station at Beulah, ND. Start-up scheduled in the spring of 1981.	N/A	Sodium Carbonate	
	Commercial: 65,000 acfm industrial system for Celanese Corp. Spray dryer pulse-jet baghouse system.	Celanese Corp. textile plant, Cumberland, Maryland. Start-up scheduled for early 1980.	N/A	Lime	

Research

As mentioned above, initial test work by B&W at Basin Electric's William J. Neal station near Velva, North Dakota was with a Hitachi two-fluid nozzle in a vertical reactor. When this configuration proved inadequate, B&W went to a modified "Y-jet" steam-atomized oil burner for slurry atomization. Flue gas enters the reactor through registers or vanes, which impart a spinning motion to the flue gas around the nozzle area. The reactor itself is a box designed to give proper retention time. Some dried sorbent drops into hoppers at the bottom of the horizontal reactor, while the remainder is collected with fly ash in a precipitator or baghouse.

The pilot unit at Velva was rated at a nominal 8000 acfm gas flow. Only ESP collection was tested with the "Y-jet" unit. The Hitachi reactor had been tested with both ESP and baghouse collection, but B&W felt they could safely operate with lower dryer outlet temperatures using an ESP collector than with a baghouse collector. The increase in sorbent utilization resulting from operating the spray dryer outlet nearer to saturation was apparently greater than that corresponding to reaction on a bag surface. Reagents tested included soda ash, pebble lime, hydrated lime, ammonia addition with lime reagent, and precipitated limestone.

The pilot plant in Velva has been shut down and is currently being dismantled. Research work is being continued with a 5×10^6 Btu/hr (1500 acfm) combustor using a single reactor with one nozzle. As well as doing full parametric studies, B&W hopes to achieve an increased understanding of the SO_2 removal reaction mechanisms in the spray dryer with this unit.

Commercial Status

Following the work at Neal Station, B&W successfully bid on the FGD system for Basin Electric's Laramie River Station Unit 3, a 500-MW unit to be built near Wheatland, Wyoming. Engineering activities for the Laramie River Station are on schedule with construction slated to begin soon. The unit is scheduled to go into commercial operation in April, 1982.

The system at Laramie River will consist of four reactors each followed by an electrostatic precipitator. Normal plant operation will call for the use of three reactors, with one as a spare. Double louver dampers (1 set isolation, 1 set control) regulate flow to the modules, with one set on each reactor inlet and a downstream set on each ESP outlet. Air flow control to individual "burners" in each reactor is set by vanes in the distribution box. A first pass on the vane design for Laramie River has been model-tested to give equal flows (within one percent) to the burners.

Each reactor will be equipped with 12 "Y-jet" nozzles in three rows of four nozzles. Reactor size was chosen to correspond to the size of the ESP used. B&W precipitators of the same size and design as those on the existing Laramie River Units 1 and 2 will be used. Units 1 and 2 use wet limestone FGD systems.

The turndown ratio for individual "burners" or "Y-jet" nozzles on the Laramie River design is about 2:1 with the fixed registers and relatively low nozzle ΔP employed. By using variable registers and higher design ΔP, a greater individual turndown ratio could have been achieved. The nozzles to be used at Laramie River will weigh approximately 64 pounds and will take one to two men from 2 to 5 minutes to change.

The Laramie River design employs no recycle, even though the coal contains a theoretical 4.5:1 Ca/S ratio. The design calls for 90 percent SO_2 removal at maximum fuel sulfur and flow rate, with a maximum stoichiometry of 1.12 based on entering sulfur. The gases leaving the spray dryer will be 10°F above saturation; 3 percent hot gas bypass will raise the dryer outlet temperature 15°F before gases enter ESP. The Laramie River design calls for 30,000 lb/hr of 150 psig steam with 50°F superheat for atomization. The capital cost for this system was reported to be $49 million in a paper presented by Basin Electric at EPA's Fifth Flue Gas Desulfurization Symposium, March, 1979 (Ref. 11). A flow diagram of the Laramie River dry FGD system is shown in Figure 5-1.

Although a demonstration and not strictly a commercial FGD system, a 120,000-acfm reactor (about 40 MWe) is scheduled for start up at Pacific Power and Light's Jim Bridger Station in late 1979. Tests have been delayed due to a boiler outage. The reactor will treat a slipstream of flue gas from a 600-MW boiler fired with a low sulfur Wyoming coal (about 450 ppm SO_2) and return the treated gas to one of six ESPs. Slipstreams from this reactor will be treated by a nominal 4000 to 5000 acfm baghouse and a 5000 to 6000 acfm pilot ESP. This demonstration will use one six-nozzle reactor with the same automatic control system proposed in the Laramie River design. It will provide a check on the control logic for Laramie River. The system will have no hot gas by-pass, as Laramie River will have. Baseline parametric studies will be with lime reagent, but the utility is interested in testing ammonia addition, soda ash, and an available waste sodium-based liquor. Basin Electric is also interested in comparing the results of the pilot ESP testing on the spray dryer outlet with some original pilot ESP data used for the design of the full-scale precipitators for the Laramie River Station. B&W will operate the spray dryer and pilot ESP for 4 to 6 months for their baseline testing, but can extend its operation if the utility funds additional testing. During baseline testing, the target SO_2 removal is the 85 percent required at Laramie River.

Testing is proceeding on a 1500-acfm pilot unit at B&W's Alliance, Ohio research facility. The unit, intended for parametric studies, uses a single Y-jet nozzle in the reactor, with a cyclone for particulate collection. Plans call for the addition of an ESP and a baghouse. Initial plans call for several coals to be tested and flue gas SO_2 concentrations of 500 ppm to 2000 or perhaps 3000 ppm. Lime reagent will be used, and test parameters include inlet and outlet gas temperatures, sorbent stoichiometry, and recycle schemes. A paste slaker will be used for fresh limes. Tests on low sulfur lignite (0.5%S), low sulfur sub-bituminous (0.9%S), and low sulfur bituminous (2.2%S) coals have been completed. Detailed results of completed test work are not available at this time, although an internal report is being prepared.

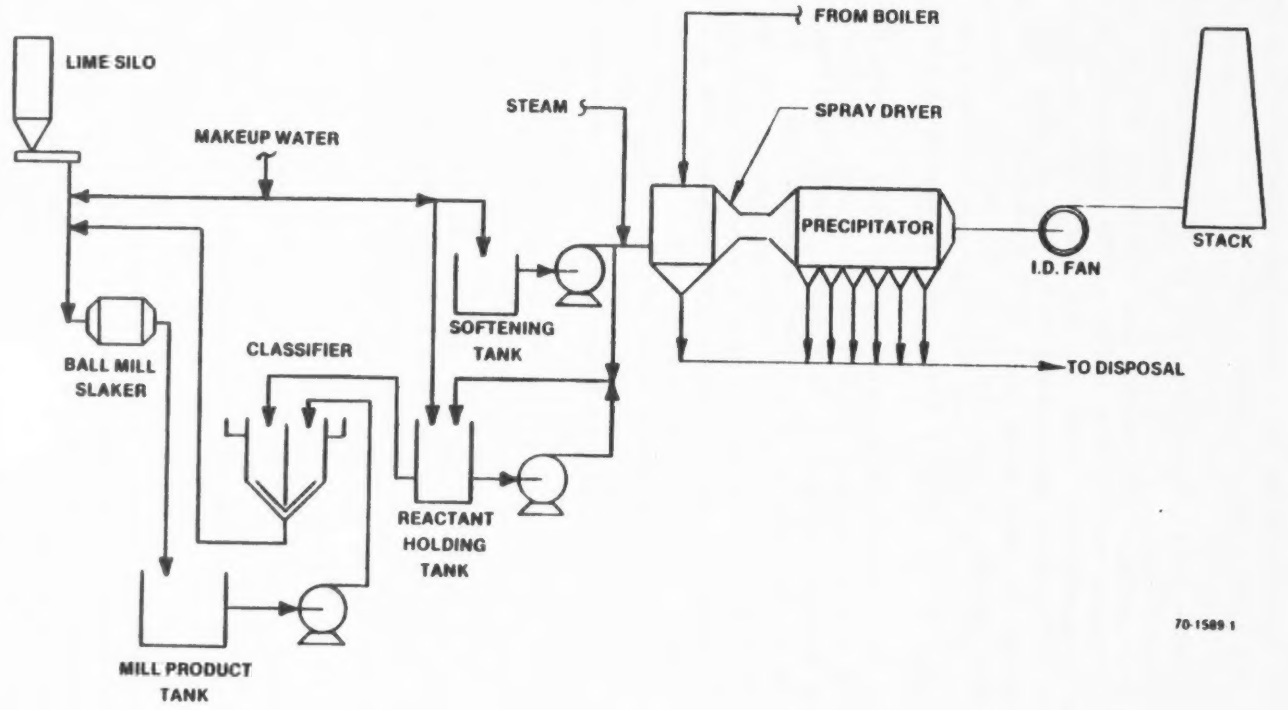
FROM BOILER
LIME SILO
STEAM
SPRAY DRYER
MAKEUP WATER
PRECIPITATOR
STACK
I.D. FAN
SOFTENING TANK
BALL MILL SLAKER
CLASSIFIER
TO DISPOSAL
REACTANT HOLDING TANK
MILL PRODUCT TANK
70-1589 1

Figure 5-1. Laramie River Station flow diagram.

Earlier research work indicated that recycled flyash/spent sorbent mixtures were more reactive when mechanically ground to smaller particle size than when reslurried directly. Consequently, some recycle work will be done with the ball mill slaker from the now disassembled Velva pilot plant used to reduce the particle size of recycled material.

One additional anticipated result of this test program is that B&W expects to derive a better understanding of the SO_2 reaction mechanisms in the spray dryer. B&W feels that neither gas-liquid reaction where absorbed gas phase SO_2 reacts with alkaline droplets, nor gas-solid reaction where flue gas SO_2 adsorbs onto dried alkaline solids can account for all of the SO_2 removal. Currently, they expect to find that chemisorption of SO_2 across several molecular layers of residual moisture on spray dried alkaline material will account for a major portion of the SO_2 removal.

Continuing work will focus on validating the preliminary reaction mechanisms that have been formulated to date. Immediate plans are to burn oil and spike the flue gas with SO_2, with a possibility of testing high sulfur fuels in the near future. B&W also plans to add a baghouse downstream of the spray dryer to compare SO_2 and particulate removal efficiencies to those obtained with the spray dryer/cyclone configuration. Longer range plans include burning different fuels and the investigation of the SO_2 removal capabilities of virgin flyash in a spray dryer system.

B&W has submitted 5 bids, all currently under evaluation with awards expected in the next few months. Also, 4 or 5 bids are being prepared for submission by the end of the year. B&W feels that the economic considerations involved in selecting FGD systems for low sulfur Western coal applications favor dry systems such as theirs.

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Slack, A. V. "Lime Scrubbing by 'Dry Processes'." A. V. Slack Report #62, January 1979, pp. 15-30.

5.2 BUELL/ANHYDRO AND EPA/BUELL

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EPA Project Officer
(919) 541-2683

Commercial Activities -
Mr. Lloyd Hemenway
Buell Emission Control Division
(717) 272-2001

Background

Buell, a division of Envirotech Corporation, has two dry FGD efforts underway. One is a totally in-house development of a dry injection/baghouse collection system which would use a Buell bag collector. In the other, Buell is working with Anhydro, a Copenhagen-based spray dryer company which began as a spin-off from Niro Atomizer, to develop a spray dryer/baghouse system. Test work on both systems will be conducted at the City of Colorado Springs' Martin Drake Station.

Research

EPA-funded test work on a 3000 acfm dry injection/baghouse system at the City of Colorado Springs Martin Drake Station was due to start in late October. The test work will investigate three sodium-based sorbents: nahcolite, raw trona ore, and upgraded trona. The parametric testing, to be conducted through December 1979, will include investigation of various stochiometric ratios (0.7, 1.0 and 1.5), inlet gas temperatures (325, 425 and 500°F), and inlet SO_2 concentrations (400 to 600 ppm). The fuel used in the Martin Drake unit is a Colorado bituminous coal with a higher heating value of about 12000 BTU/lb and a sulfur content of from 0.3 to 0.7%. The nahcolite to be used in the tests has been obtained from a Bureau of Mines pilot shaft sunk in a Colorado nahcolite/oil shale deposit near Denver. The nahcolite from this mine will be made available for government and industry dry FGD test work. This pilot shaft is currently one of the few available sources of nahcolite. A final report on this dry injection work is expected in early 1980.

Buell is also conducting EPA-funded waste disposal studies. The major process to be studied is sintering of the dry waste product, based on the sinterna process (patented by Industrial Resources, Inc.). The waste disposal studies are expected to last for about nine months and are being performed by Battelle Memorial Institute (Columbus Laboratories) under a subcontract from Buell.

In a parallel privately funded research program, Buell and Anhydro are developing a dry FGD system with a spray dryer and baghouse. Initial work with both lime and soda ash sorbents, was done at Anydro's Copenhagen facility with a 3000-acfm spray dryer. Future plans are to conduct EPA-funded demonstration studies on a 20000 acfm spray dryer/baghouse system at the Martin Drake Station. The spray dryer, supplied by Anhydro under an exclusive technological agreement, is a 13-ft diameter tower equipped with a rotary atomizer. Sorbents to be tested include lime and the three sodium-based sorbents used in the dry injection studies. Recycling of the spent sorbent-flyash products will also be investigated. The spray dryer/baghouse system is expected to start up in December 1979, and tests will be run for 6 months to a year. The primary purpose of the unit will be to obtain design data for development of a full-scale spray dryer system.

Buell/Anhydro has submitted a detailed technical paper on their spray dryer/baghouse system that will appear in the December 1979 issue of the Air Pollution Control Association Journal. Buell also plans to set up a scale model of a 20000 acfm lime-based spray dryer/baghouse system at the American Chemical Society Chemical Show in New York, December 3-5, 1979.

Commercial Status

At this point Buell's top priority is the completion of test work on the spray dryer and dry injection systems at Martin Drake. Buell has invited several architect-engineer (A-E) firms to visit the facility in late January and February of 1980. Buell plans to rely heavily on presentations to A-E's and utilities in marketing their spray dryer system.

The Buell/Anhydro joint venture has submitted five budgetary prices to utilities for spray drying systems. They have also submitted a budgetary price for one industrial application and bid on another industrial application.

Information Sources

Blythe, Gary. Meeting Notes at Buell, Lebanon, PA, June 29, 1979.

Kelly, Mary E. Telephone conversation with Dale Furlong, Buell Envirotech R & D, October 11, 1979.

Kelly, Mary E. Telephone conversation with Lloyd Hemenway, Buell Environtech, October 11, 1979.

5.3 COMBUSTION ENGINEERING

Address: C-E Power Systems
Combustion Engineering, Inc.
1000 Prospect Hill Road
Windsor, Connecticut 06095

Contact For More Information: Kal W. Malki
System Design
Environmental Systems Division
(203) 688-1911

Background

Combustion Engineering has conducted several in-house studies related to dry FGD. In 1972 they studied sludge drying as a dewatering method, and they have an ongoing program studying char-ash drying in the C-E coal gasification process. C-E has also studied an ammonium sulfate dry SO_2 scrubbing process available from a licensor.

Regarding a lime-based dry FGD system, CE has gone through a literature survey and a study of available pilot data. They have tested several atomizing devices, presumably for use in a spray dryer, and have completed a conceptual design of a lime-based dry FGD system.

Research

As a result of the above, C-E has begun test work on a pilot unit consisting of a 20,000 acfm C-E spray dryer equipped with a two-fluid nozzle atomizer using air as the atomizing fluid. The spray dryer is followed by a fabric filter and ESP in parallel. The pilot unit will be installed at the Northern States Power Sherbourne County Unit #1, which burns Sarpy Creek (Montana) coal (1.0 percent sulfur, 10 percent ash, 8000 Btu/lb). The pilot unit will use lime as a sorbent. Test work will involve parametric studies of temperatures, air-to-cloth ratios, L/G ratios, SO_2 levels, scrubber velocity, and recycle of spent sorbent/fly ash mixtures. In conjunction with this pilot program, C-E is also planning a dry scrubbing waste disposal study.

In the future C-E plans to continue pilot plant testing of their spray dryer system although no definite plans were disclosed at this time. C-E is currently preparing bids for two dry FGD systems for utility applications.

Information Sources

Blythe, Gary. Telephone conversation with K. W. Malki, C-E, June 6, 1979.

Malki, K. W. C-E System Design, personal communication with Gary Blythe, July 11, 1979.

Kelly, M. E. Telephone conversation with Kal Malki, C-E System Design, October 11, 1979.

5.4 DOE/GRAND FORKS ENERGY TECHNOLOGY CENTER

Address: Grand Forks Energy Technology Center
Grand Forks, N.D. 58201

Contact For More Information: Harvey Ness
Grand Forks Energy Technology Center
(701) 795-8000

Background

Grand Forks Energy Technology Center (GFETC) has been conducting research on dry injection systems on the 200 scfm scale, comparing nahcolite and trona sorbents. Parameters being investigated include inlet SO_2 concentration, inlet gas temperature, bag materials, air-to-cloth ratios, and the sequencing of sorbent addition and bag cleaning cycles. SO_2 removal efficiencies of up to 90 percent have been achieved with nahcolite at 50 to 60 percent sorbent utilization, with the lower sorbent utilization observed at a high air-to-cloth ratio.

Research

Dry injection test work on the 200 scfm scale is expected to be completed in early 1980. Tests to optimize performance with trona have been completed. Test work to optimize performance with nahcolite is proceeding after some delay in obtaining nahcolite. (A Bureau of Mines pilot shaft near Denver has provided a new source of nahcolite.) SO_2 levels representative of low-sulfur Western coals, up to 1500 ppm SO_2 on a dry basis, are being investigated in the current test work. A final report is expected by mid 1980.

Research conducted at GFETC has indicated that trona is somewhat less reactive than nahcolite as an SO_2 sorbent. This diminished reactivity can be explained in terms of specific surface area (m^2/g). At equivalent conditions of temperature and time, GFETC studies have shown that nahcolite has a significantly larger surface area (7.0 m^2/g vs 5.0 m^2/g at 500°F and 30 minutes activation time). The difference is greatest at high temperatures and long activation times. The GFETC investigators suggest that it is possible that the use of a sorbent with a smaller particle size, injection at elevated temperatures, and operation of the baghouse at the highest practical temperatures would overcome the apparent lower reactivity of trona enough to make it "a practical alternative to nahcolite" for use in dry injection/baghouse systems.

GFETC is planning to expand their current dry injection program in the near future. They are presently designing a 150 scfm baghouse that will be dedicated to dry injection tests (the current baghouse is also used for particulate characterization studies). The new baghouse will be a pulse-jet type. Plans are to test both nahcolite and trona sorbents while varying parameters such as temperature, residence time (air-to-cloth ratio), and stoichiometry. Higher SO_2 levels, above 1500 ppm, may also be investigated. Bench scale waste disposal studies have been completed and a final report is being prepared.

Future Research Plans

In addition to dry injection work, Grand Forks will be involved with the Rockwell-Wheelabrator Frye spray dryer/baghouse FGD system being constructed at Otter Tail Power's Coyote Station. GFETC will sample for particulate and SO_2 removal efficiencies. In addition, they are currently negotiating with Otter Tail Power to determine the ranges in which GFTEC will be allowed to vary such parameters as temperature and sorbent feed rate to characterize the FGD system. The Coyote station FGD system is scheduled to start up in the spring of 1981. As a supplement to the proposed test work at Coyote Station, Grand Forks is conducting conceptual and small scale laboratory studies to investigate large-scale recovery of sodium from the spent sorbent/fly ash mixture for reinjection into the system. The advantage of sodium recovery is seen as two-fold: (1) it will help to stabilize the waste products by reducing their soluble sodium content, and (2) reinjection of recovered sodium will reduce fresh sorbent consumption, which would provide considerable savings in operating costs.

As a final note on dry injection, there remain uncertainties in both trona and nahcolite availability. In the case of trona, depletion allowance complications may keep trona from being available in the quantities needed for full-scale dry injection systems. The new Bureau of Mines pilot shaft is currently the only available source of nahcolite.

Information Sources

Ness, H. M., Stanley Selle, DOE /GFETC and Oscar Manz, University of North Dakota. Power Plant Flue Gas Desulfurization for Low-Rank Western Coals, presented at the 1979 Lignite Symposium, Grand Forks, ND, May 30-31, 1979.

Blythe, Gary. Telephone conversation with Stanley J. Selle, DOE, June 7, 1979.

Blythe, Gary. Telephone conversation with Harvey Ness, DOE, July 3, 1979.

Kelly, M. E. Telephone conversation with Harvey Ness, DOE, October 16, 1979.

5.5 DOE/MORGANTOWN ENERGY TECHNOLOGY CENTER

Address: Morgantown Energy Technology Center
Morgantown, West Virginia 26505

Contact For More Information: Dr. Charter Steinspring
Exploratory Research Group
(304) 599-7546

Background

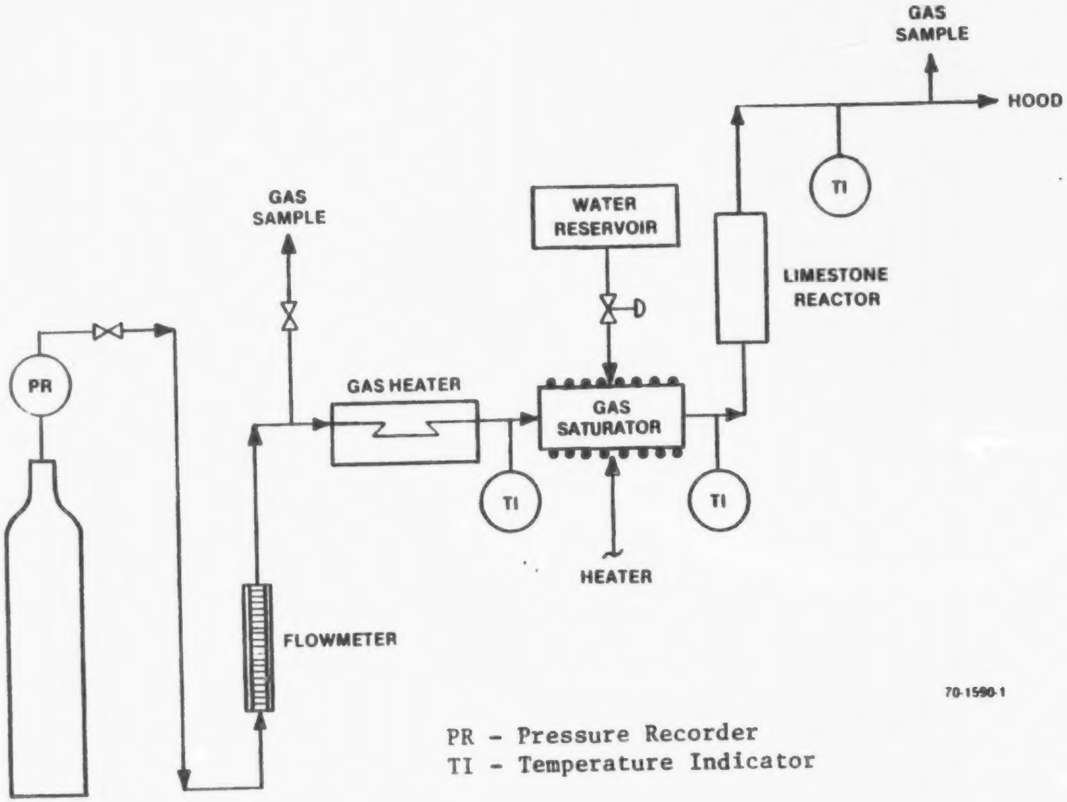
The use of powdered dry lime or limestone in dry injection/baghouse systems has resulted in much lower removal efficiencies than in systems where sodium-based sorbents, such as nahcolite and trona, have been used. However, the waste solids from sodium alkali-based processes are water soluble and pose potential disposal problems, whereas calcium-based product solids are considerably more stable. Studies have been underway at Morgantown Energy Technology Center (METC) to develop a "dry" limestone FGD process.

Research

A patented technique, involving the addition of water vapor to hot flue gas (300°F) to increase the saturation temperature of the gas above a critical minimum before it is passed over a bed of limestone chips to remove the SO_2, was developed by Shale and Cross in 1976. Both laboratory kinetic studies and bulk evaluation studies have been conducted. Figure 5-2 is a flowsheet for the bulk evaluation tests for this "modified dry" limestone process (MDLP).

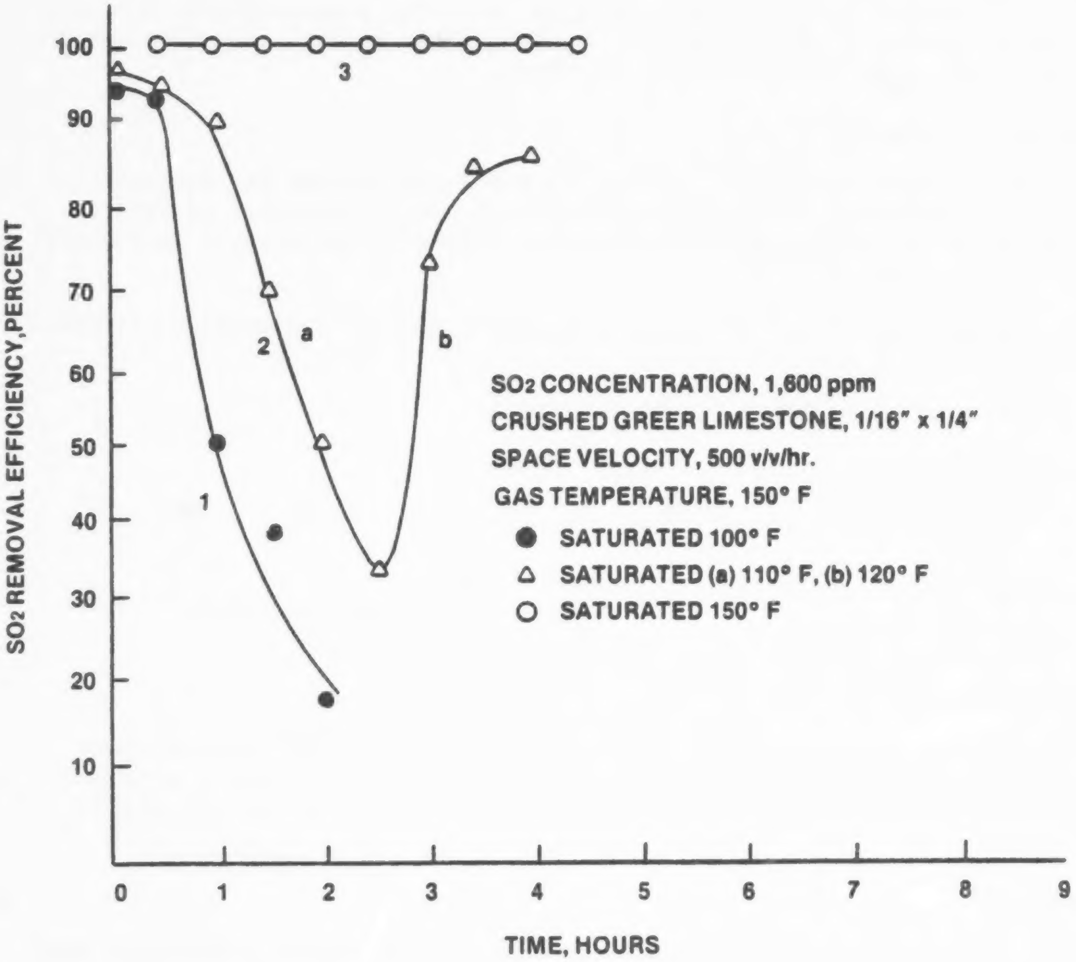
Results of the kinetic studies show reaction rates equivalent to those found in high temperature fluid bed processes involving calcined limestone. Other results of the kinetic studies showed that reaction occurred on the limestone chip surface and that calcium sulfate was the major product.

In the bulk evaluation studies, simulated dry flue gas was heated to 280°F and passed through the saturator prior to entry into the bed of crushed limestone. The gas entered the bed at a temperature of 150° to 160°F and a space velocity of 500/hr. Tests were conducted using limestone beds 1-inch in diameter and 9 inches deep and ½-inch diameter by 4 inches deep. Limestone chips were 1/16-inch by ½-inch. Figure 5-3 shows results of bulk evaluation studies with 1600 ppm inlet SO_2 in the gas at 150°F. At a saturation temperature of 150°F, a SO_2 removal efficiency of greater than 90% was maintained for over 3 hours. At lower saturation temperatures (i.e., 100° to 110°F), removal efficiency decreased rapidly with time due to the formation of a $CaSO_3/CaSO_4$ layer on the pellet after an initial period of high removal. Experiments at higher space velocity (4000/hr) have shown that SO_2 removal efficiencies of greater than 90% can be achieved when the water vapor saturation temperature of the gas, controlled by the addition of water in the saturator, is no more than 30°F below the actual gas temperature entering the limestone bed. Sorbent utilization is reported to be "less than 90%".


GAS
SAMPLE
HOOD
TI
LIMESTONE
REACTOR
WATER
RESERVOIR
GAS
SAMPLE
PR
GAS HEATER
GAS
SATURATOR
TI
TI
HEATER
FLOWMETER
70-1590-1

PR - Pressure Recorder
TI - Temperature Indicator

Figure 5-2 Flow sheet for bulk evaluation studies of modified dry limestone process



70-1591-1

Figure 5-3 Effect of moisture on SO_2 removal in a fixed limestone bed.

Current Status

Mr. Shale retired from METC in September, 1979. At the present time no further work is being carried out on the "modified dry" limestone process, although studies to investigate the limestone/SO_2 reaction mechanism are being conducted.

The data from Mr. Shale's test work has been verified for accuracy, but a complete interpretation of the results has not been conducted. Preliminary economic analyses, based on both the kinetic and bulk evaluation studies employing a counterflow moving-bed reactor, have shown the capital and operating costs for the MDLP to be greater than those for a conventional wet lime/limestone process. The excess cost is due in part to the large pressure drop characteristics of counter-flow moving-beds.

Information Sources

Shale, C. C. and G. W. Stewart, "A New Technique for Dry Removal of SO_2", DOE/Morgantown Energy Technology Center, paper presented at Second Symposium on the Transfer and Utilization of Particulate Control Technology. Denver, CO, July, 1979.

Kelly, M.E. Telephone conversation with Charter Steinspring, DOE/METC, October 18, 1979.

5.6 DOE/PITTSBURGH ENERGY TECHNOLOGY CENTER

Address Pittsburgh Energy Technology Center
4800 Forbes Road
Pittsburgh, Pennsylvania 15213

Contact For More Information: Mr. Richard Dempski
Pittsburgh Energy Technology Center
(412) 675-5730

Background

DOE's Pittsburgh Energy Technology Center (PETC) has had a program underway for several months to evaluate dry injection of various sorbents. They have a 500 lb/hr coal furnace that provides the flue gas for their testing.

Research

PETC's initial testing has focused on moderate sulfur Pittsburgh seam coals (1.5-2%S). System parameters that were evaluated include sorbent type, stoichiometry, sorbent feed mechanism, and sorbent particle size. Four sorbents are being tested: sodium carbonate, sodium bicarbonate, nahcolite, and trona. Data from this test program is still under evaluation, but preliminary results have shown greater than 90 percent SO_2 removal with sorbent stoichiometries of up to 2. Pressure drop through the baghouse was reported to vary from about 10-14 inches of water.

Future Research

Future research plans are to continue evaluation of the system for SO_2 removal from higher sulfur coals. PETC also has requested bids for the construction of a spray dryer which they hop to have installed by mid-1980. Testing of the spray dryer system will begin the second half of 1980.

Information Sources

Dickerman, J. C. Telephone conversation with Richard Dempski, PETC January 2, 1980.

5.7 ECOLAIRE

Address: Ecolaire Systems, Inc.
Two Country View Road
Great Valley Corporate Center
Malvern, PA 19355

Contact For More Information: Carl Newman
Vice-President of Engineering
(215) 648-8600

Terry McRae
Senior Vice President
(415) 676-6315

Background

Ecolaire Systems is part of the Ecolaire Corporation which was founded in 1971. The Ecolaire Corporation includes several companies which have been in the business of supplying equipment to the utility industry for many years. These companies include the following:

Research

Ecolaire Systems has had no previous dry FGD research and development program other than Industrial Clean Air (a subsidiary of Ecolaire Corporation) experience with dry additives for enhancement of bag filter performance. However, Ecolaire has constructed a 10,000 cfm mobile pilot plant for demonstration of a spray dryer/baghouse FGD system. When completed, and mobile plant can be trucked to any location on six semitrailers and erected in a 60-ft by 60-ft area in approximately a two-week hookup time. The unit under construction uses an Ecolaire-modified Niro atomizer spray dryer and an ICA four-section baghouse using 12-in. diameter by 36-ft long bags. Design data for system bidding will come from the mobile demonstration unit, illustrated in Figure 5-4.

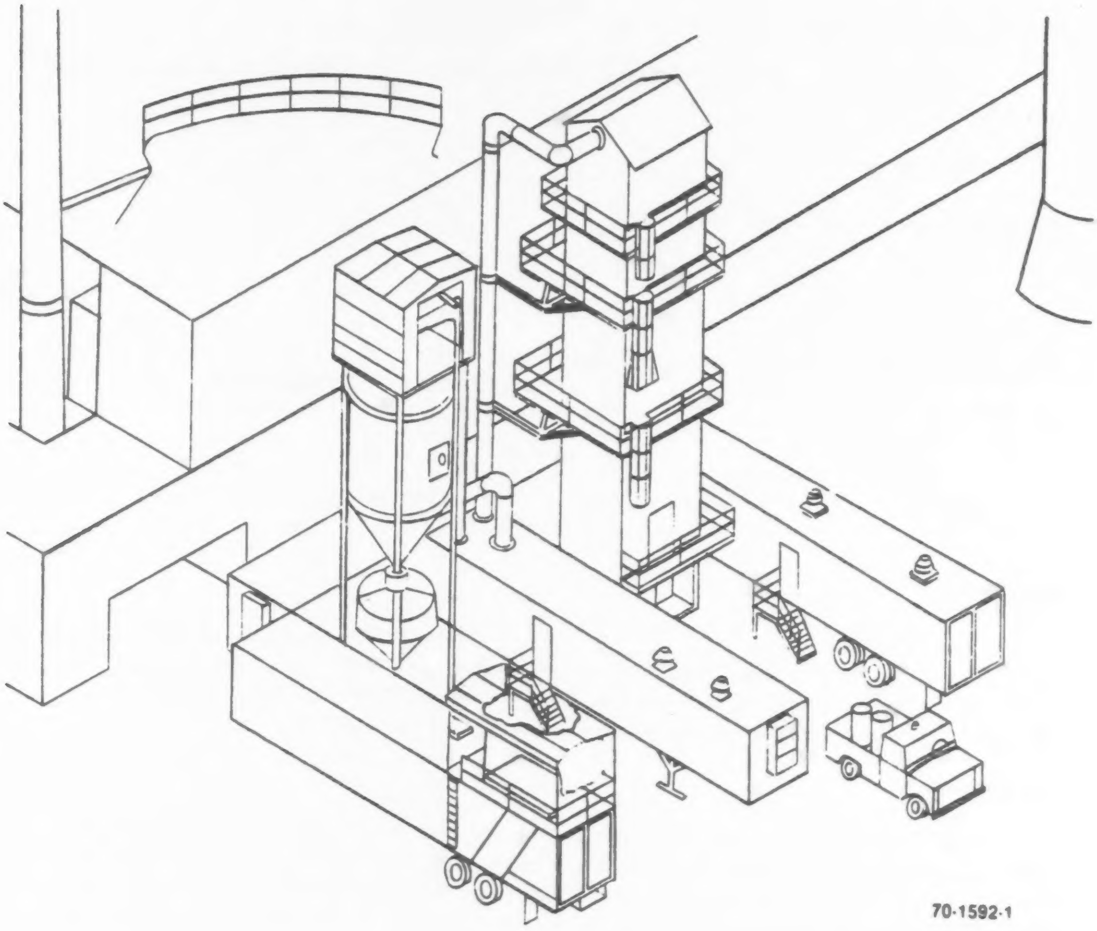


Figure 5-4 Ecolaire's mobile demonstration dry FGD unit.

The mobile unit has been set up at Nebraska Public Power District's Gerrel Gentleman Unit 1. System start-up is scheduled for late 1979. Ecolaire plans to conduct parametric and design optimization studies for up to 4 months. They will be investigating both rotary and nozzle atomization. The primary sorbent to be tested is lime and provisions have been made for investigating recycle of spent sorbent/fly ash mixtures. Other parameters that will be varied include inlet SO_2 concentration (up to 2000 ppm SO_2), inlet gas temperature, temperature drop over the spray dryer, and sorbent concentration.

Commercial Status

Ecolaire Systems will not bid on a utility or industrial system until they have design data available from their mobile demonstration unit. Current thinking for a commercial system would call for four or five spray dryer modules, each with five rotary or nozzle atomizers. Primary control on the system would be outlet gas temperature, which sets the water rate to the scrubber. Sorbent concentration would be controlled based on inlet and outlet SO_2 concentrations, boiler load, etc. Perhaps a minicomputer would be used to calculate required sorbent concentration based on these various inputs. The control system would be designed by Ecolaire Systems, using purchased components.

Although the mobile demonstration unit uses a modified Niro spray dryer, Ecolaire has no agreement with a spray dryer manufacturer for exclusive use of their equipment. By not making direct ties with a spray dryer company, Ecolaire feels they have more flexibility in providing the best system for an individual application by choosing among any number of commercially offered spray dryers.

Information Sources

Blythe, Gary. Meeting Notes, meeting at Ecolaire Systems, Inc., Malvern, PA., May 22, 1979.

Kelly, M.E. Telephone conversation with Carl Newman, Ecolaire. November, 1979.

5.8 ENERGY AND POLLUTION CONTROLS, INC.

Address: Energy and Pollution Controls, Inc.
Subsidiary of Flick-Reedy, Inc.
7N015 York Road
Bensenville, Ill. 60106

Contact For More Information: Grant Hollett, Jr.
Energy and Pollution Controls
(312) 766-3400

Background

EPC is a recently formed subsidiary of Flick-Reedy, Inc. They have developed a totally dry FGD reactor system for industrial applications.

Research

Development work on the EPC-designed reactor illustrated in Figure 5-5 was started in early 1978. This dry FGD reactor is intended for combination with a baghouse to result in a totally dry FGD system for industrial applications. The reactor is designed for cyclonic flow of flue gas near a hydraulically driven "slinger", which distributes dry hydrated lime in a direction countercurrent to the flue gas flow. Hydrated lime is fed to the slinger with a commercially available dry chemical feeder. Directly above the slinger is an air-operated eductor which captures and recirculates the lighter fraction of the partially spent sorbent. Below the reaction section of the reactor, a conical expansion reduces the flue gas velocity to allow dropout of heavy particulate matter before the gas flows to a bag collector.

Gas velocities in ductwork to and from the reactor are typically 8 to 12 ft/sec. Velocities inside the reactor vary from approximately 25 ft/sec. in the cyclonic section down to approximately 5 ft/sec. in the expansion section.

Development work on the reactor used flue gas from a coal-fired (1.6 million Btu/hr hot water boiler) burning a 3.3 percent sulfur Illionis coal. Flue gas sulfur content varied from 1600 to 2300 ppm SO_2. Flue gas temperatures in the reactor varied from 350°F to 500°F. but temperatures to the downstream cartridge filtration device were limited to 350°F to protect the NOMEX cartridge. The speed of the slinger was not specified, due to patent considerations. Pressure drop across the reactor in all tests was less than 0.5 inches of water. SO_2 removal efficiencies varied from 45 percent to 95 percent at 0.8 to 3.0 times the stoichiometric ratio. Table 5-2 summarizes the SO_2 removal results of dry reactor test work.

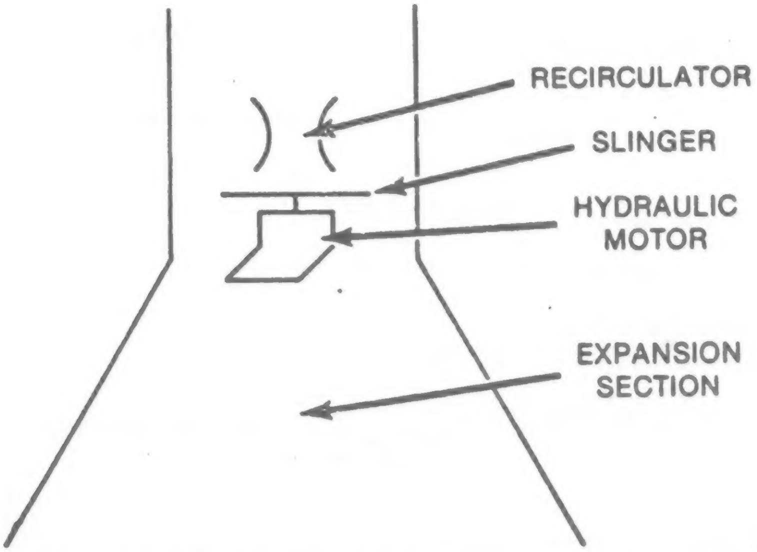


Figure 5-5. Air pollution control (SO_2) reactor for dry reagent

TABLE 5-2 DRY REACTOR CHRONOLOGICAL TEST SUMMARY AUGUST 1978 - OCTOBER 1978

Material	Stoichiometric ratio	Inlet SO_2 Concentration (ppm)	Outlet SO_2 Concentration (ppm)	Removal efficiency (%)
Lime (hydrated)	3	1600	400	75
Lime (hydrated) (a)	3	2000	180	91
Lime (hydrated)	2.5	2000	400	80
Lime (hydrated)	0.8	2000	1100	45
Lime (hydrated)	2	1800	400	78
Lime (hydrated)	1.5	2300	750	67
Lime (hydrated) (b)	1	2000	700	65
Lime (hydrated) (c)	1.5	1700	200	88
Lime (hydrated) (d)	1.5	2000	1100	45
Lime (hydrated) (e)	1.5	2000	100	95

Notes:

a. Half was added at point approximately 5 ft upstream of reactor.

b. Half was added at point approximately 5 ft upstream of reactor. Inspection revealed accumulative pile in duct at end of test.

c. After 10 minutes flow, efficiency rose to 95%.

d. Geometry of lower section of reactor was modified.

e. Slinger speed (RPM) varied from other tests.

Commercial Status

EPC will market the reactor for industrial applications. They report that capital and operating costs for SO_2 and particulate control using their dry system will be approximately half those for a system using a wet scrubber, on a dollars per ton of coal basis.

Preliminary design has been completed for construction of a commercial model (25,000 acfm) for Kerr Industries in South Carolina. This unit will be used in EPA sponsored tests at Kerr to be performed by Environmental Testing, Inc. The tests are scheduled to begin March, 1980.

Information Sources

Blythe, Gary. Telephone conversation with Grant Hollett, Jr., EPC, June 4, 1979.

Hollett, Grant T., Jr. "Dry Removal of SO_2 Applications to Industrial Coal Fired Boilers." Presented at APCA Convention, Cincinnati, Ohio, June 25-28, 1979.

Kelly, M.E. Telephone conversations with Grant Hollett, Jr., EPC, October 5 and October 26, 1979.

5.9 EPA/BATTELLE-COLUMBUS LABS

Addresses: Industrial Environmental Research Laboratory
U.S. Environmental Protection Agency
Research Triangle Park, NC 27711

Battelle-Columbus Labs
405 King Avenue
Columbus, OH 43201

Contact For More Information: J. H. Wasser
EPA, Project Officer
(919) 541-2476

Robert Giammar
Battelle
(614) 424-7701

Background Information:

As part of an EPA-funded program to evaluate industrial coal-fired stoker boilers, Battelle developed a limestone/high sulfur coal pellet in an attempt to control SO_2 emissions. Initial tests were conducted in a model 20 bhp spreader-stoker boiler using a pellet with a Ca:S mole ratio of 7:1. Preliminary results indicated that 70 to 80% retention of the available sulfur in the fuel was achievable, however, the increased particulate emissions resulted in an opacity increase from a normal 4 to 7 percent up to 22-25 percent. In an effort to reduce the increased particulate emissions that result from firing the limestone/coal pellet, Battelle began development and testing of a 3.5:1 Ca:S pellet.

Research

The newly developed pellet (Ca:S ratio of 3.5:1) has mechanical strength, durability, and weatherability characteristics comparable to that of raw coal. Laboratory tests in the 20 bhp model spreader stoker and in a fixed-bed reactor have resulted in 60 to 80 percent retention of the available sulfure in the fuel. A high sulfur Illinois coal was used for these tests. Laboratory tests are continuing in preparation for a 1-day test to be conducted in late 1979 to evaluate firing the pellet in Battelle's 25000 lb./hr steam boiler at the Columbus lab facilities. The 1-day test will investigate combustion characteristics and sulfur retention capabilities of the pellet with a Ca:S mole ratio of 3.5:1 as well as determine the effects of the pellets on boiler operation. With regard to boiler operation, one preliminary hypothesis is that the limestone present in the pellet may result in higher ash fusion temperatures, thus helping to reduce the clinker formation tendency of the coal.

In other on-going work, bench-scale waste disposal studies conducted by Battelle have shown that the ash produced from combustion of the coal/limestone pellet does not exhibit the same acid-leaching characteristics as fly ash from straight coal combustion. Battelle is also beginning reaction mechanism studies to determine the details of the SO_2 removal reaction in the stoker bed. Plans are to use scanning electron microscope techniques to determine what compounds are being formed and to identify their structures.

Preliminary cost estimates have been prepared and have been confirmed in further economic studies that indicate the cost of producing the coal/limestone pellet will be about $15/ton. This cost includes both capital and operating costs for grinding and pelletizing and reagent costs for the binder and limestone.

Future Research

Future work including a 30-day full scale demonstration test on a 75,000 lb steam/hr boiler is currently under funding evaluation by the EPA. The results of the present study will be evaluated to determine their potential impact on the nation's energy supply and pollution standards.

Information Sources

Giammar, Robert D., et al, "Evaluation of Emissions and Control Technology for Industrial Stoker Boilers," in Proceedings of the Third Stationary Source Combustion Symposium, Vol. 1, EPA-600/7-79-050a, February, 1979.

Kelly, M. E. Telephone conversation with Robert Giammar, Battelle-Columbus labs, October 10, 1979.

Kelly, M. E., Telephone conversation with J. H. Wasser, EPA, October 11, 1979.

5.10 EPA/ENERGY AND ENVIRONMENTAL RESEARCH CORP. (EERC)

Address: Industrial Environmental Research Laboratory
U.S. Environmental Protection Agency
Research Triangle Park, N.C. 27711

Contact For More Information: Blair Martin
EPA Project Director
(919) 541-2235

Background

EERC conducted a preliminary feasibility study as part of a program to test EPA's concept of limestone injection into a low-NO$_x$ burner for SO$_2$ removal. Initial test work at the 1×10^6 Btu/hr heat input rate was promising, and work is continuing on a smaller (70,000 Btu/hr) scale.

Research

In this process, limestone is mixed and pulverized with coal prior to combustion and fired through a B&W low-NO$_x$ burner. Sulfur contained in the fuel reacts with the limestone present to form calcium salts which are collected with the fly ash emitted from the boiler.

The B&W low-NO$_x$ burner system consists of two physically isolated combustion zones: a fuel-rich water-cooled primary combustion furnace and a secondary furnace where combustion products from the first furnace mix with the air necessary to complete combustion. EERC has measured the retention of sulfur resulting when limestone or trona is mixed with coal prior to combustion in the burner. The effectiveness of alkali addition to this type of burner is apparently related to the lower flame temperature resulting from the two-stage combustion as compared to conventional combustion. The lower temperature keeps the particles from approaching their melting temperatures, which can result in a glazing of the surface of the reagent particles that produce relatively unreactive particles.

EERC has noted that sulfur retention effectiveness is dependent upon good mixing of the reagent with the coal. They have found that adding reagent to the coal prior to passing the coal through the pulverizer substantially improves SO$_2$ removal. The pulverizer, which is designed for 75 percent minus 200 mesh, is believed to promote good mixing between the reagent and coal. EERC has also noted that sulfur retention can be greatly influenced by combustion conditions in general.

The test work so far has been very preliminary in nature. Table 5-3 indicates the SO$_2$ removal which has been achieved.

Future Research

As a result of these initially favorable performance data, EERC has proposed a full parametric study of sulfur retention in three sequential combustor sizes: 70 thousand Btu/hr, 10 million Btu/hr, and 50 million Btu/hr. These proposals are currently under review by EPA. There have apparently been no cost estimates yet made for this process due to its early stages of development.

TABLE 5-3. SO_2 REMOVAL IN THE EERC LOW-NO_x COAL BURNER

Basis: Utah Low Sulfur Coal

Reagent	Reagent/Sulfur Mole Ratio	Percent Removed
Limestone	1	53
	2	73
	3	88
Trona	2	41
	4	80

Information Sources

Blythe, Gary. Telephone conversation with Bill Nurick, EERC, July 25, 1979.

Jones, D. J. Personal communication with Ted Phillips, Pacific Power & Light, March 1979.

Kelly, M. E. Telephone conversation with Blair Martin, EPA, October 1, 1979.

5.11 EPA/KERR INDUSTRIES

Address: Industrial Environmental Research Labs
Particulate Technology Branch
U.S. Environmental Protection Agency
Research Triangle Park, NC 27711

Contact For More Information: Jim Turner
EPA Project Officer
(919) 541-2925

Background

EPA is funding dry FGD test work at a Kerr Industries textile finishing plant in South Carolina. The major portion of the test work will focus on Energy and Pollution Control Inc.'s "dry pollution control reactor", (see Section 5.9).

Research

A baghouse fire has delayed testing of this sytem. Test work is scheduled to begin in March, 1980, to evaluate dry FGD system which will treat 25000 acfm of flue gas (about 4 MW). The baghouses (modified reverse air and pulse-jet) will be operated at air-to-cloth ratios of from 3 to 6 and both high and low inlet SO_2 concentrations will be tested. Lime and limestone sorbents will be used.

Information Sources:

Blythe, Gary. Telephone conversation with Jim Turner, EPA, June 25, 1979.

Kelly, M. E. Telephone conversation with Jim Turner, EPA, November 7, 1979.

5.12 JOY/NIRO JOINT VENTURE

Address: Joy Industrial Equipment Company
Western Precipitation Division
4565 Colorado Boulevard
Los Angeles, California 90039

Niro Atomizer, Inc.
9165 Rumsey Road
Columbia, Maryland 21045

Contact For More Information: Jim Meyler
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Background

Niro supplies some 75 percent of the world's spray dryer needs. Spray dryer applications include: instant milk, instant coffee, pvc, floor tile ceramics, kaolin, dyestuffs, copper and nickel sulfide for smelting applications, and raw cements. The kaolin plants are significant because they involve large (30-ft diameter) dryers that approach the size of those in utility FGD applications. The smelting operations are significant because some use flue gases from coal-fired generating stations for process heating and thus operations follow boiler load as would a utility FGD spray dryer. Many of the cement plant installations also use coal-fired flue gases for process heating.

Niro began test work using a spray dryer for FGD and HCl removal applications in their Copenhagen research facility in 1974. In this test work they made several hundred test runs at 1000 to 3000 acfm using lime, limestone, sodium carbonate, and magnesium oxide as sorbents. As a result of this test work, Niro sold a small (2000 to 3000 acfm) spray dryer to Fiat of Milan, Italy, which used sodium carbonate to remove SO_2 from flue gas. In November 1977, Niro entered into a 2-year agreement with Joy Manufacturing to develop and market a spray dryer-based FGD system which employs baghouse or ESP particulate collection. The agreement has since been extended another 5 years.

Research

The Joy/Niro joint venture team was invited by Basin Electric to pilot a spray dryer-based dry FGD system at their Antelope Valley Station. In mid-November 1977, design work was begun on a pilot unit to be built at Otter Tail Power's Hoot Lake station. The pilot unit included a 20,000-acfm spray dryer followed by a 3000-acfm electrostatic precipitator and a 9000-acfm baghouse in parallel. The baghouse had four compartments and 60 one-foot diameter bags. The pilot unit was constructed from late November to mid-February, and first operated from mid-February to April 24, 1978. During this period sodium carbonate and lime sorbents were tested, and design data were acquired for use in preparing a bid for the Basin Electric Antelope Valley Station FGD system. Parametric studies of the effects of inlet and outlet temperatures, stoichiometric ratio, recycle techniques, and particulate collector type on SO_2 removal were included in this test work. A 100-hr demonstration run of the pilot unit at Antelope Valley design conditions was also included.

Niro and Joy returned to Hoot Lake in mid-September 1978 to acquire data for preparing a bid on Basin Electric's Laramie River Station and to verify data from the previous test work. During this mid-September to mid-December 1978 test period,some 30 to 40 thousand data points on FGD performance were acquired. Also,during this period rail cars of Laramie River coal were shipped to Hoot Lake to operate the 60-MW Unit 2 boiler for several days at Laramie River conditions. The Laramie River ash was reported to be quite cementitious, but no operating problems were incurred during this period. Some tests were conducted adding water treatment sludge to the atomizer feed, and this was found to be a suitable method of disposal for the sludge. Some testing was conducted with commercially available ground limestone as a sorbent with very limited success. Other testing included SO_2 spiking up to a 4500 ppm flue gas concentration.

All current FGD research activities are being done on a new FGD pilot unit at the Niro Copenhagen research facilities. After substantial testing at Hoot Lake, Niro feels that parametric, research-oriented testing can best be done at their facility. Site specifics, such as fly ash alkalinity effects, can be evaluated by fly ash injection. The 5000 acfm test facility uses a propane burner as the source of flue gas. Both reverse air and pulse jet baghouses can be tested. Provisions have been made for spiking with fly ash, SO_2, SO_3 and steam to stimulate any flue gas condition.

The primary use of the Copenhagen facility is to obtain site specific information on SO_2 removal and fly ash reactivity for responding to bids. In addition, Niro is also looking at the chemistry and reaction mechanism of the SO_2 sorption reaction. Results of this test work are for internal use only, but they may use these results to prepare papers for presentation at upcoming symposia.

Commercial Status

Following the pilot program at Fergus Falls, the Joy/Niro joint venture successfully bid on the FGD system for Basin Electric's Antelope Valley Station Unit 1, the first of two 440-MW stations to go in near Beulah, North Dakota. The Western Precipitation Division of Joy Industrial Equipment Company was awarded the contract with Niro Atomizer Company as prime subcontractor. Construction of the Antelope Valley FGD system is reported to be on schedule with start-up planned for the spring of 1982. Figure 5-6 depicts the Antelope Valley dry FGD system.

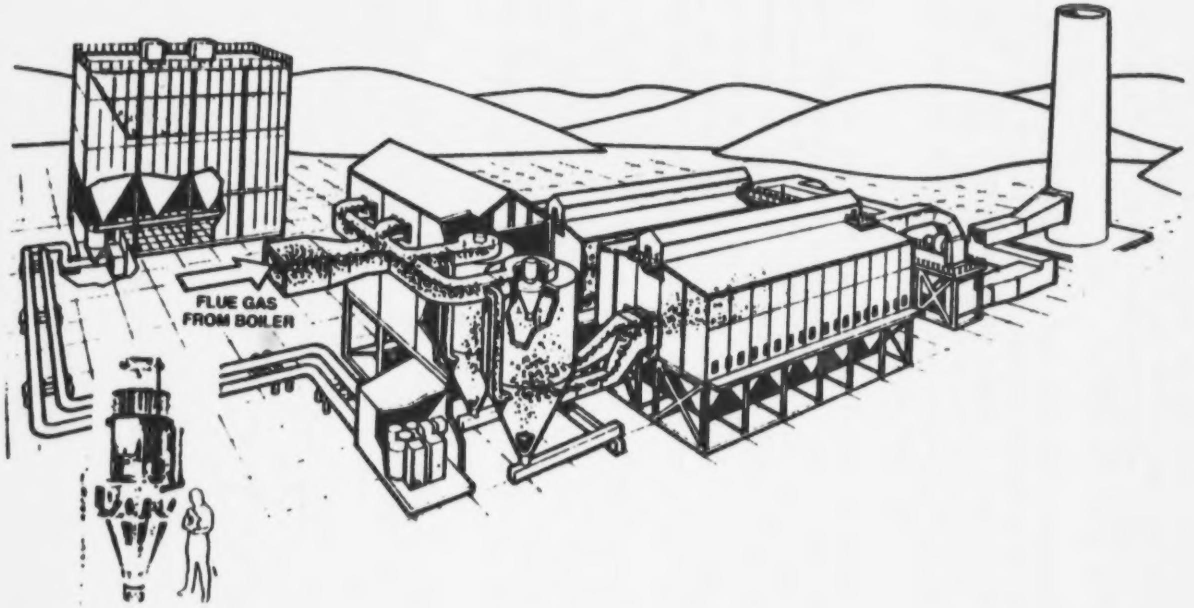
FLUE GAS
FROM BOILER

Figure 5-6. Antelope Valley Station gas cleaning system.

The Antelope Valley installation will use five 46-ft diameter dryer modules, although any four modules could handle the total flue gas volume. Each module will be equipped with one atomizer with a direct drive motor. There will be one spare atomizer for use in any of the five modules. The sorbent used will be primarily lime slaked in a ball mill slaker, although sludge from the station's primary water treatment plant and a portion of the recycled sorbent/ash mixture will be added.

The SO_2 removal guarantee with only Unit 1 operating will be 62 percent for average sulfur fuel (0.68 percent S) and 78 percent for maximum sulfur fuel (1.22 percent S). After Unit 2 comes on line over a year later, the removal guarantee will be 81 percent for average sulfur, and 89 percent for maximum sulfur. The emission limitation set by the North Dakota State Department of Health is 0.78 lb SO_2 per million Btu.

The sorbent/fly ash mixture leaving the spray dryer will be collected in a Western Precipitation baghouse. The baghouse will have 28 compartments with a total of approximately 8000 fluorocarbon-coated fiberglass bags. The bags will be 12 inches by 35 feet and will be cleaned by reverse air. The gross air-to-cloth ratio under maximum flue gas flow conditions will be 2.19:1. The bag life guarantee for the Antelope Valley system is proprietary, but the standard Western Precipitation bag life guarantee is two years.

The lime utilization is very nearly 100 percent. This high utilization is possible because of the ability to utilize available alkalinity in the fly ash through spent sorbent/fly ash recycle. Also, the spray dryer outlet temperature will be controlled to near saturation. Bypass of up to six percent of the total flue gas flow will be used to reheat the spray dryer outlet to 185°F.

The Antelope Valley FGD system will use an innovative supervisory control scheme designed by Honeywell. The computer-controlled system will monitor boiler load, inlet SO_2 level, outlet SO_2 level, and inlet and outlet spray dryer temperatures and adjust lime concentration in the spray dryer feed for minimum lime consumption required to maintain the desired SO_2 removal. Basin Electric reported the capital cost of this system to be over $49 million in a paper presented at EPA's Fifth Flue Gas Desulfurization Symposium, March 1979 (Reference 11).

Waste disposal is not included in the Joy/Niro responsibilities. Basin will return the waste product-fly ash mixture to the mine in coal trucks for underground disposal.

To date, the Antelope Valley Station is the only FGD system sold by the Joy/Niro venture. However, they currently have two bids in evaluation, one bid in-house, and expect five to six bid requests by the end of 1979.

Although it cannot be strictly considered a commercial system, Joy/Niro has been awarded a contract to provide a 100-MW demonstration spray dryer/particulate collection system to Northern States Power for their Riverside

Station. The lime-based system would treat up to 660,000 acfm of flue gas in a single 46-ft diameter spray dryer equipped with a rotary atomizer. The utility would operate the unit and participate in the demonstration R&D effort with Joy/Niro.

The flue gas to be treated is generated by burning an Eastern coal of up to three percent sulfur or a Western low sulfur coal or a mix of the two. The spray dryer/ESP system (using an existing ESP) will be completed during the summer of 1980, with a baghouse to be completed about six months later. This arrangement will permit comparison of ESP and baghouse particulate collection and SO_2 removal on a large scale unit.

Joy feels the market for utility spray drying systems is favorable. They foresee responding to five or six bids by the end of 1979. They feel the market for industrial systems will develop after promulagation of industrial boiler New Source Performance Standards.

Information Sources

Blythe, Gary. Meeting Notes, Joy, Los Angeles, CA. June 14, 1979.

Janssen, Kent and Robert L. Eriksen. "Basin Electric's Involvement with Dry Flue Gas Desulfurization," paper presented at the Fifth EPA Symposium on Flue Gas Desulfurization, Las Vegas, Nevada, March 5-8, 1979.

Dickerman, J. C. Telephone conversation with Jim Meyler, Joy, October 26, 1979.

5.13 KENNECOTT DEVELOPMENT COMPANY (ENVIRONMENTAL PRODUCTS DIVISION) (formerly Carborundum)

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Background

As Carborundum, the Environmental Products Division (EPD) conducted pilot-scale dry injection studies (1000 acfm) at their University of Tennessee facility and pilot unit tests on a 15000 acfm spray dryer/baghouse system at Basin Electric's Leland Olds Station.

Research

The Environmental Products Division is continuing pilot-scale test work

(1000 acfm) on both dry injection and spray dryer SO_2 control systems at their University of Tennessee facility. The U.T. unit is a small stoker-fired boiler burning a coal with an average sulfur content of 0.5% and a higher heating value of about 10000 Btu/lb.

Dry injection tests have been run with both sodium bicarbonate and nahcolite. Temperatures of the entering flue gas ranged between 270 and 300°F, while entering SO_2 concentrations ranged between 1000 and 4000 ppm. (Some test work has been done at the 5000 ppm SO_2 level.) In tests using relatively non-alkaline fly ash as the sorbent, 25% SO_2 removal was obtained. Results of the major portion of the test work are considered proprietary.

The Environmental Products Division is planning to start up a 1000 acfm spray dryer/baghouse system in late 1979. Sorbents to be tested include lime and soda ash. Recycle of spent sorbent/fly ash mixtures and removal efficiency at high inlet SO_2 concentrations will also be investigated.

Commercial Status

The Environmental Products Division plans to emphasize both utility and industrial applications in marketing their spray dryer-based flue gas cleaning systems. They are in the process of executing an exclusive agreement with a spray dryer company with a demonstrated background in both rotary and nozzle atomization. EPD will most likely employ rotary atomization in their lime-based spray dryer systems. As Carborundum, EPD had an agreement with DeLaval for supplying the spray dryers, however, this agreement has been terminated.

The Environmental Products group recently submitted a bid to Colorado Ute Electric Asso. for a 450 MW flue gas cleaning system. Colorado Ute is considering only dry systems for this unit. In regard to the future market for utility and industrial dry FGD systems, the Environmental Products Division sees spray dryer-based FGD systems being, at the very least, competitive with wet systems for both low and high sulfur coal applications.

Information Source

Blythe, Gary. Telephone conversation with Don Boyd, Carborundum, May 16, 1979.

Blythe, Gary. Telephone conversation with H. M. Majdeski, Carborundum, July 6, 1979.

Majdeski, H. M. Carborundum, personal correspondence with Gary Blythe, July 17, 1979.

Kelly, M. E. Telephone conversation with H. Majdeski, EPD, Kennecott Development Co., October 18, 1979.

5.14 KOCH ENGINEERING

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Summary of Activities

Koch began development of a "spray dryer based dry FGD system" in early 1979. In May 1979 Koch was reportedly about one year away from having a marketable dry FGD system.

Koch Engineering has completed studies on their spray dryer system verifying published efficiency data. They have achieved SO_2 removals comparable to literature values. (Neither sorbent type or test conditions used to achieve these removal levels were specified).

Koch plans to begin marketing their spray dryer/baghouse system in February 1980. No details on the marketing program were available due to the somewhat unique nature of the approach they plan to take.

Koch is presently conducting in-house demonstration and design studies on the 3000 to 5000 acfm scale. No test results were provided. They also plan to conduct larger scale pilot tests on an 8-ft diameter spray tower. Sorbents to be investigated include sodium hydroxide, sodium bicarbonate and lime. Initially testing will be conducted with inlet SO_2 levels representative of low-sulfur coal combustion, with plans for future testing at higher SO_2 levels.

Information Sources

Blythe, Gary. Telephone conversation with Ahmed Akacem, Koch Engineering, May 16, 1976.

Kelly, M. E. Telephone conversation with Ahmed Akacem, Koch Engineering, October 19, 1979.

5.15 MIKROPUL

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Background

Mikropul is a division of U.S. Filter, which includes Ducon, the wet scrubber manufacturer. Mikropul was originally in the pulverizing business and was called Pulverizing Machinery Company. Mikropul's air pollution equipment business was a result of the necessity to control pulverizing emissions. Their first equipment was a fabric blow ring collector dating back to the 40's. A version of their current continuous pulse jet baghouse was introduced in 1957. Since then nearly 200 installations around the world have been put into service with Mikropul Pulsejet bag collectors for recovery of the spray dried product. In the early 1970's, Mikropul began work in the pure dry scrubbing business, designing and installing equipment using dry alumina to control fluoride emissions from aluminum smelters. In these applications, fluid bed feeders are used to introduce fresh and recycled alumina to a reactor to contact fluoride-containing flue gases. Some 70 percent of the fluoride removal occurs in the reactor, the remaining 30 percent occurs on the downstream bag collectors. Pulse jet bags, rather than reverse air or shaker bags are employed, partly because they provide for more turbulent gas/solid contact in the vicinity of the bag.

Their largest installation at Ormet Aluminum in Hannibal, Ohio treats 2.6×10^6 acfm, using 144 pulse jet bag modules containing some 55,000 bags and around 1000 pulse jet valves. Six reactors are used, and some reactant captured on the bags is recycled to improve overall sorbent utilization. Total Mikropul installed dry scrubbing equipment worldwide treats 12×10^6 acfm. Mikropul has also sold dry systems which use dry hydrated lime to remove fluorides from a gas stream in a glass manufacturing facility.

Research

A sister company to Mikropul, Filtrol, a refining catalyst manufacturer, has participated with Mikropul in identifying possible dry FGD sorbents for evaluation in pilot-or bench-scale dry injection/baghouse collection facilities. They have tested zeolites, which unfortunately selectively remove water before SO_2. Of the common dry FGD sorbents, Mikropul has only tested sodium bicarbonate: seventy percent SO_2 removal was obtained at flue gas containing 1600 to 2000 ppm SO_2 at 300°F.[2]

Mikropul began work on a spray dryer-based FGD system in January 1978. Bayliss Industries supplied the spray dryer technology. Besides lime studies, Mikropul has evaluated zinc oxide wastes as an FGD sorbent. Over 50 percent SO_2 removal with a ZnO slurry feed to a spray dryer system was obtained.

Mikropul's current test facility at Summit NJ includes a small nozzle atomization spray dryer which discharges to a small pulse jet bag collector. Flue gas is supplied by a gas burner. Provisions are available to spike the flue gas in the 1000 acfm unit with SO_2, moisture, and fly ash from the Mercer generating station. Another U.S. Filter subsidiary, Drew Chemical, is working with Mikropul to provide lime slurry additives. Drew Chemical has provided polyelectrolyte additives which reduce lime slurry settling tendencies and improve atomization in a spray dryer by acting as surfactants.

As the result of their spray dryer work, Mikropul was awarded a contract in late 1978 to provide a spray dryer/baghouse on an industrial coal-fired boiler at Strathmore Paper Company, a subsidiary of Hammermill, Inc., at Woronoco, Mass. Their agreement with Strathmore allows Mikropul to vary numerous parameters during a six-month test period in order to establish a data base for future designs. The system is lime-based and the single spray dryer will use multi-fluid nozzles for atomization. A pulse jet baghouse will be used. Provisions for solids recycle will exist. Parameters to be varied include reagent type, sulfur levels, slurry density and additives, slaking techniques, atomization techniques, and baghouse parameters. In addition, other collection techniques may be investigated. Table 5-4 summarizes the parameters to be varied and their ranges.

Commercial Status

As mentioned above, Mikropul has sold a lime-based spray dryer/baghouse collection FGD system to Strathmore Paper at Woronoco, MA for use on an industrial boiler. This PC boiler, which generates 90,000 lb of 675 psig steam per hour, produces 40,000 acfm at 350 to 400°F by burning 2 to 2½ percent sulfur, 9 percent ash coal. The plant must meet a Massachusetts air quality regulation of 0.55 lb SO_2 per 10^6 Btu. This fuel source can be augmented by up to 30 percent (by Btu content) #6 fuel oil. Mikropul's guarantee calls for 75 percent SO_2 removal on 3 percent sulfur coal, with a maximum stoichiometry on the order of 2.75. Pilot studies indicate 75 percent removal can be achieved at up to 2000 ppm SO_2 inlet concentration at a stoichiometry of around 1.2. Sorbent utilization has been on the order of 70 percent. Flue gas is withdrawn downstream of the boiler air heater at 350 to 400°F, but a provision is available to bypass hot flue gas if necessary.

The Mikropul system started up in September, 1979. Mikropul personnel are operating the system on a 24-hr, 7-day per week basis. They have experienced some operating problems but are in the process of correcting these by instituting design changes. Performance results are not publicly available at this time. Mikropul will continue operation of the system for optimization and establishment of a design data base. Further results may be available in early 1980.

The design details of the FGD system are considered proprietary by Mikropul, but the system can be generally described as a lime sorbent spray dryer followed by a Mikro-Pulseair pulse jet bag collector. Spent reactant and fly ash disposal will be handled by the paper company. Figure 5-7 illustrates a general Mikropul dry FGD system similar to that at Strathmore paper.

TABLE 5-4 SPRAY DRYER TEST VARIABLES
STRATHMORE PAPER COMPANY

Parameter	Range of variation
Sorbent	High calcium granular limes. High calcium pebble lime. Dolomitic lime.
Fuel Sulfur content (%)	Eastern Coal 2 to 2 1/2 % (nominal) 4% (maximum at Mikropul Expense) Fuel Oil 0.7 to 2%
Slurry density	10 wt % solids desired, up to 20% as needed.
Recycle	From baghouse product, amount to be determined.
Slurry additives	Various polyelectrolytes, varied concentrations (on the order of 2 g/10 gal H_2O).
Air-to-cloth ratio	3.2:1 to perhaps 7:1, as success dictates.
Materials of construction	Various metal coupons to be placed in dryer, ducts, and baghouse for periodic examination.
Disposal techniques	Evaluate suitability as feed to Portland cement plant. Determine best landfill treatment methods (e.g., treatment in pug mill to wet and compact).
Atomization technique	Steam and air atomization at various rates
Collection technique	May evaluate ESP collection on a slipstream. Most tests will use baghouse.
Slaking technique	Evaluate effect of slaking techniques on reactivity of dolomitic lime, which has shown lower reactivity than high Ca^{++} limes (apparently due to poor reactivity of commercially slaked MgO content)

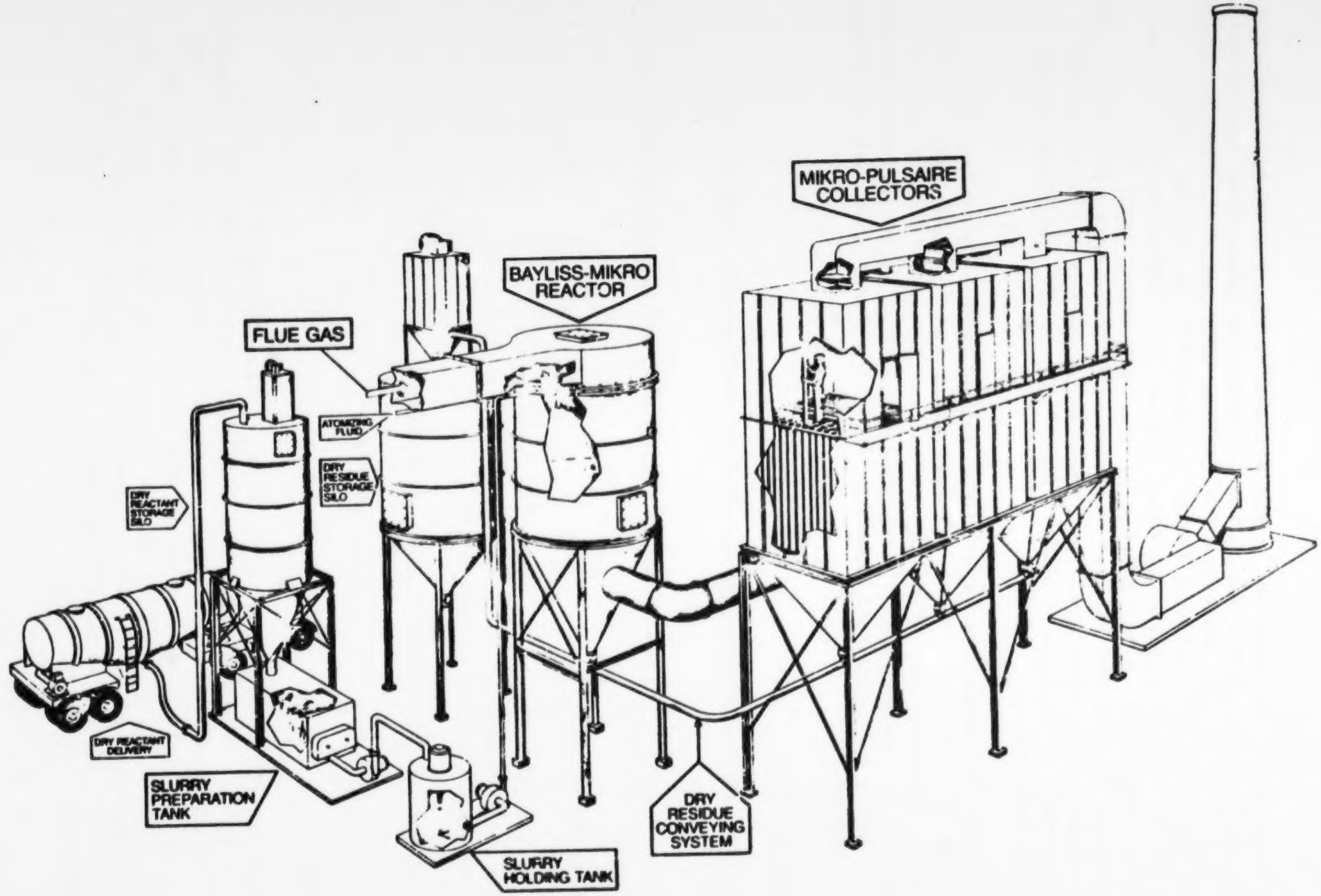
MIKRO-PULSAIRE COLLECTORS
BAYLISS-MIKRO REACTOR
FLUE GAS
ATOMIZING FLUID
DRY RESIDUE STORAGE SILO
DRY REACTANT STORAGE SILO
DRY REACTANT DELIVERY
SLURRY PREPARATION TANK
SLURRY HOLDING TANK
DRY RESIDUE CONVEYING SYSTEM

Figure 5-7. Mikropul spray dryer/baghouse dry FGD system.

A third party is involved in the Strathmore Paper project: Lucien J. Luckel, an engineering constructor with an extensive background in industrial boilers, is providing the expertise for dealing with industrial boiler clients, as well as designing all interfaces and tie-ins with the boiler itself. Mikropul has no immediate plans to enter the utility boiler market, but may in the future depending on the success of the Strathmore Paper unit. If Mikropul should go into the utility business, the third party providing the interface capabilities with utility clients would be another U.S. Filter company, Resource Scientists of Tulsa, which has utility engineering and construction experience.

In a utility design, a reverse air rather than a pulse jet bag collector may be required. The break-even point for the two types is about 200,000 acfm, (applications where the pulse jet can operate at an air-to-cloth ratio of 3.4 times that of a reverse air unit). Mikropul has installed reverse air units at a Southern Colorado Utilities power plant and on several industrial boilers.

Information Source

Blythe, Gary. Meeting Notes, meeting at Mikropul, Summit, NJ, May 24, 1979.

Blythe, Gary. Telephone conversation with Tom Reinauer, Mikropul Corp., October 25, 1979.

5.16 RESEARCH-COTTRELL

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Background

Previous FGD work by Research-Cottrell has focused on wet lime/limestone systems. The only previous purely dry FGD work done by a Research-Cottrell company has been that done by their wholly-owned subsidiary, KVB. A spray dryer/baghouse pilot system at the Texas Utilities Big Brown unit is the first major dry FGD effort by the Research-Cottrell R&D group. This spray dryer/baghouse pilot dry FGD program will evaluate several sorbents. Research-Cottrell has an exclusive agreement with Komline-Sanderson for use of their spray dryer in a dry FGD system.

Research

Research-Cottrell has completed pilot unit studies with lime at the Texas Utilities Big Brown unit (10,000 acfm). Details of the test work are considered proprietary at this time. A final report on the test work should be completed by December 1979 and Research-Cottrell may present the results at a seminar or conference. Research-Cottrell's wholly owned subsidiary, KVB, has completed an Electric Power Research Institute (EPRI) funded study on dry injection with the results scheduled for publication in the near future.

Commercial Status

Now that pilot unit testing is completed, Research-Cottrell (RC) is ready to offer a commercial spray dryer/baghouse system. They are confident of scaling up design data from 10000 acfm because they have scaled up wet system designs for up to 3000 MW worth of FGD from 5000-10,000 acfm pilot data. For a utility size installation, Research Cottrell anticipates using multiple atomizers per dryer vessel. The designs of the reagent feed system and the slaker, fan, dampers, and other overall system components will be based on Research-Cottrell's wet FGD system experience. Research-Cottrell has in-house nozzle atomization experience, and if a sodium system is ever required, nozzle atomization would probably be used. Rotary atomizers are believed superior in a calcium system because they are less susceptible to pluggage and erosion than nozzles. Plans are to operate the spray dryer outlet at about 50°F above adiabatic saturation to avoid flue gas buoyancy and collector bag problems.

Information Source

Blythe, Gary. Meeting at Research-Cottrell, Sommerville, NJ, May 23, 1979.

Kelly, M.E. Telephone conversation with Kishor Parikh, Research-Cottrell, October 18, 1979.

5.17 ROCKWELL INTERNATIONAL/WHEELABRATOR-FRYE JOINT VENTURE

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Background

For the past eight years, Rockwell International has been developing their sodium carbonate-based regenerative Aqueous Carbonate Process which uses a spray dryer as a flue gas contactor. A simplification of the process excludes regeneration and instead involves operation in an open loop manner as a "throwaway" process. Employing the open loop portion of the Aqueous Carbonate Process (ACP), Rockwell and Wheelabrator-Frye have jointly developed a two-stage dry scrubbing process where an alkaline solution or slurry is introduced into a spray dryer contactor, and dry reaction products and fly ash are collected by a fabric filter. Rockwell successfully demonstrated the open loop portion of the ACP in a 7-ft diameter dryer at the Southern California Edison Mohave Station in 1972. Flue gas was taken downstream of the station's electrostatic precipitators and contacted with a sodium carbonate solution in the spray dryer.

Wheelabrator-Frye piloted a dry injection/baghouse collection FGD system at the Basin Electric Leland Olds station using nahcolite as a sorbent. When it became evident that nahcolite supplies would not be available in commercial quantities in the near future, the Rockwell open loop ACP spray drying concept was combined with the Wheelabrator-Frye baghouse that provided spent sorbent and fly ash collection. It was found that the SO_2 removal by the open loop portion of the Rockwell ACP was not as sensitive to sorbent type as was dry injection; yet, it still retained the desired dry collection feature. Initial testing was with sodium-based sorbents, although lime was later found to be a suitable sorbent.

In all spray dryer-based FGD development work and in commercial sales, Rockwell has used exclusively Bowen Engineering spray drying equipment. Although the Rockwell-Wheelabrator Frye joint venture developed the two-stage process, Bowen Engineering has an exclusive agreement to provide spray drying equipment.

Research

The spray dryer/baghouse pilot unit at Leland Olds was dismantled in September 1978 after 16 months of operation. During this period Rockwell/Wheelabrator studied a variety of sorbents, with some sorbent recycling, at SO_2 levels from 700 to 3000 ppm.

There are ongoing studies at Bowen's facilities in New Jersey using a 7-ft dryer and a Mikropul pulse-jet collector. Flue gas is from an auxiliary burner with SO_2 and fly ash spiking provisions.

Rockwell has completed testing on their portable pilot plant unit at Northern States Power's Sherbourne County station and at Pacific Power and Light's Jim Bridger Station. This unit uses a 7-ft dryer with a pulse jet bag collector and has provisions for warm gas bypass. At Jim Bridger, a pilot ESP which was originally used to design the existing precipitators is available to test a spray dryer/ESP system. Fortunately, this Flakt pilot

ESP unit is about the same size as the portable test unit (approximately 5000 cfm).

Additional pilot unit testing has begun at Commonwealth Edison's Joliet Station. The Joliet pilot unit is to be flexible enough for full parametric studies. The unit uses a 7-ft, 4000 to 5000 acfm spray dryer, with provisions for using either a reverse-air, off-line cleaning baghouse or a pulse jet, continuous flow baghouse as well as provisions for an electrostatic precipitator. The unit will have provisions for both warm and hot gas bypass and sorbent/fly ash recycle. Most work will be done with lime sorbent, but some soda ash studies may be made. The Joliet plant burns varying mixtures of four Western subbituminous coals, 8000 to 9000 Btu/lb, 0.5 to 1 percent sulfur. Testing will last 1 to 2 years.

Other test work being conducted by Rockwell includes bid support studies on their spray dryer at their California facility and periodic design studies on a 7-ft diameter dryer at Bowen labs in New Jersey. Rockwell is also negotiating a site for testing lime-based system for high sulfur Eastern coal applications.

Other Rockwell research includes studies in waste disposal. These studies show that for nearby disposal (up to 1 mile), pneumatic conveying may be the most economical method of transportation of waste material. For longer distances, pelletizing or briquetting of wastes may be required to permit open trucking. This operation could be accomplished for about $1.25 per ton (operating and capital). The resulting briquette may be unleachable due to fusing. The only binder material required would be water.

Rockwell has also looked into reuse schemes. By adding a proportionate amount of water to the waste material, it sets up resulting in load bearing properties of around 500 lb/in^2. Permeability of the product is less than 1 ft/yr (10^{-7} cm/sec). Some of the waste materials may be useful as a concrete additive.

Commercial Activities

Following the research work at Leland Olds, the Rockwell/Wheelabrator-Frye joint venture was awarded a turnkey subcontract for the furnishing, fabrication, delivery, erection, and successful operation of a complete emissions control system for the Coyote plant. The Coyote Station is a 410-MW lignite-fired unit to be located near Beulah, North Dakota. The station is to be owned by a consortium of five North Dakota and Minnesota power companies. Otter Tail Power Company is to operate the plant.

The 410-MW Coyote Station FGD system is designed for 70 percent SO_2 removal for all fuels. Guaranteed sorbent utilization is 80 percent, a conservative value for this high utilization sodium-based system.

Design of the Coyote Station calls for an air preheater outlet temperature of 285°F. The stack gas must exit at 185°F. These conditions are not optiumum for spray dryer performance; 185°F is 50° to 60°F above adiabatic saturation. The design temperature seems somewhat low as most lignite-fired boilers experience air preheater exit temperatures of 325 to 350°F. Rockwell does not expect any ash alkalinity utilization in the design since there is no ash recycle and reaction of solid phase fly ash alkalinity with SO_2 is minimal.

The Coyote Station will use four 46-ft dryers, each with three 150-hp atomizers (although at design conditions each will draw only 83hp). The primary control variable of the system will be dryer outlet temperature. Outlet dew point will also be measured and used for setting approach to dew point on the outlet. Dryer outlet and stack SO_2 will have a narrow range of control on sorbent feed rate. In other words, if the outlet SO_2 level is well below the control point, the SO_2 input to the sorbent feed control would make a small decrease in the feed rate. If outlet SO_2 level was a primary control point, the sorbent feed rate might be shut off completely until the outlet SO_2 increased sufficiently.

Bag temperature will be limited by an internal bypass between the inlet and outlet plenums on the baghouse. These bypass dampers will be set to open if the baghouse inlet temperature exceeds a maximum set point. The baghouse will use a synthetic fabric, such as Dacron, and will operate at a net air-to-cloth ratio of 2.7 to 1. This involves a total of 28 compartments, with two off for maintenance and two off for cleaning at a given time.

Rockwell will use no control valves in slurry service. All slurry feed rates will be set by progressive cavity pumps (such as Moyno) with variable speed drives. There will be no flue gas flow dampers or control valves. The air distribution through the FGD system is controlled by careful design of the ductwork. The dryer vessels are designed with three atomizers per vessel. The atomizers are placed a standard distance from the vessel wall to avoid wall wetting. No agglomeration problems on overlap of spray patterns from the three atomizers are foreseen. In tests using three atomizers in a 7-ft dryer with extensive spray pattern overlap, virtually the same SO_2 removal was measured as would be achieved using a single atomizer flowing the same amount of sorbent. In 1/16th-scale air flow testing of the Coyote ductwork design, they found they were able to distribute equal flow to four dryers within two percent and equal flow to three atomizers in a dryer to within two percent. Bowen feels the three-atomizer approach is advantageous because loss of an atomizer would not result in loss of a whole dryer module. Although the use of multiple atomizers has not been demonstrated at the 500,000 acfm level, Bowen has demonstrated flowing 1/3 of the total design gas flow (170,000 acfm) to a single atomizer.

The Coyote plant will use coal trucks to return waste sorbent/fly ash to the mine. The material will be handled in the dry form, using dustless loading equipment. Design of this equipment is not within the Rockwell battery limits, however.

Construction on the Coyote plant is well underway. On site, foundations and considerable structural steel are in place. Off site, fabrication is proceeding on dryer vessels. The plant should start up by the spring of 1981. Start up will more than likely be with commercial soda ash. Rockwell is currently looking into alternate sources of lower quality sodium products for use as sorbent at Coyote. Sources from both the Green River, Wyoming area and the Owens Lake, California area are being pursued. One source would involve a material that is roughly 50 percent Na_2CO_3 at a cost of $13/ton. On a cost per ton of Na_2CO_3 equivalent, this is less than half the $60+/ton of commercial sodium carbonate. Of course, shipping costs for the less pure product would be greater due to the greater quantities involved. Soda ash will be stored on site at Coyote as a sodium carbonate monohydrate slurry, with water circulated through the storage tanks. Feed to the spray dryers will be saturated sodium carbonate monohydrate solution from these tanks, which is diluted to achieve the desired spray dryer temperature. Soda ash will be stored as a monohydrate slurry rather than as the anhydrous solid because the monohydrate slurry has a bulk density of 71 lb/ft^3 versus 55 lb/ft^3 for commercial dry soda ash.

The Rockwell/Wheelabrator-Frye joint venture has also sold an industrial dry FGD system to Celanese Corporation. The Celanese project involves treating flue gas from a stoker-fired industrial boiler in Cumberland, Maryland. Currently, the boiler is slated to burn 1 to 2 percent sulfur coal but may go to a 3 to 4 percent sulfur West Virginia coal. The flue gas flow rate is 65,000 acfm at 350°. The Rockwell system will use lime sorbent with no recycle of sorbent/fly ash. SO_2 removal will be 70 to 80 percent for 1 to 2 percent coal, higher for 3 to 4 percent coal. Sorbent utilization will be on the order of 70 to 80 percent. Particulate collection will be with a pulse jet, continuous type collector. Lime slaking will be accomplished with a "pore tube" slaker. Construction of this system is on schedule, with start-up planned for January 1980.

As far as other commercial sales, Rockwell has two bids under evaluation and one bid being prepared. Rockwell expects to bid on up to six more utility dry FGD systems for Western low sulfur coal or lignite applications, by the end of 1979.

Rockwell has a standard approach to a dry system design. First, determination is made whether a "standard" system will work. This involves approximately a 40°F approach to dew point, no recycle, no gas bypass, and preferably about 90 percent sorbent utilization. If this is unattainable, then warm gas bypass is tried taking a small amount of flue gas after the air preheater and routing it around the spray dryer to reheat from a closer-than-40°F approach to dewpoint. If this is insufficient, hot gas bypass is included taking flue gas upstream of the air preheater for reheat. There is a penalty associated with hot gas as bypass approximating 0.5 percent of the total fuel rate to the boiler if 5 percent of the gas flow is bypassed. Recycle, considered to be a supplement to any of the above designs, can be used to get an apparent sorbent utilization of greater than one. Recycle of fly ash and partially spent sorbent can result in both improved dryer performance and improved filter performance for a combined synergistic effect. Rockwell designs recycle equipment as an "add on" with a minimum of redundancy (minimum first cost). Adding recycle provisions might add about two percent to the total equipment cost.

Rockwell reports that for large Eastern applications, the cost of lime reagent is a major factor in the viability of dry systems. In utility high sulfur applications, the cost differential between lime in a dry system and limestone in a wet system can mean sorbent savings of millions of dollars a year for the wet limestone system. This puts the operating economics of a dry system at a disadvantage for these applications. A scheme for using a limestone sorbent in a dry system could greatly improve the economics. Rockwell sees the application of dry FGD to Eastern applications as focal point of future R&D efforts.

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APPENDIX A

CONVERSION FACTORS

1 ft = 0.3048 meter

1 short ton = 0.91 metric ton

1 lb = 0.454 kg

1 gal = 3.79 liters

1000 cfm = 0.5 m^3/s

1 gal/1000 ft^3 = 0.13 liters/m^3

1 BTU = 0.252 kcal